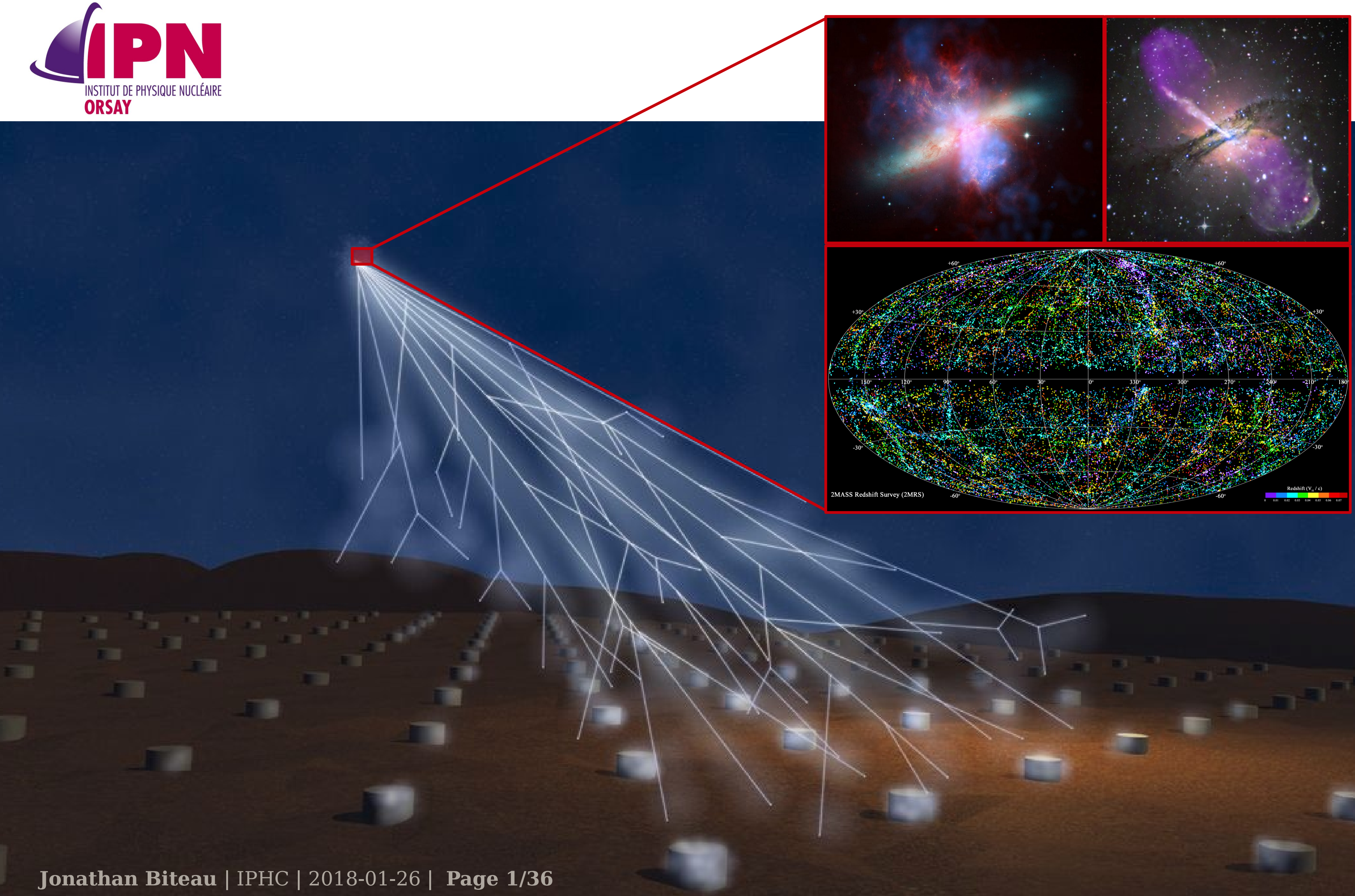
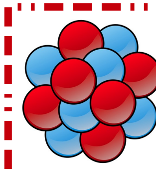
# Anisotropies at ultra-high energies
# An indication and a discovery



# Ultra-high energy cosmic rays


## UHECR ID



**Nature**

Stable nuclei: p to Fe

**Energy**

from $10^{18}$ to $>10^{20}$ eV
1 **E**eV to >100 **E**eV

millions to billions TeV!
*note: 1 J ~ 6 EeV*

**Flux**

>10 EeV: few / km² /year
>50 EeV: few / km² / century
*nearly isotropic*

**Travel distance**

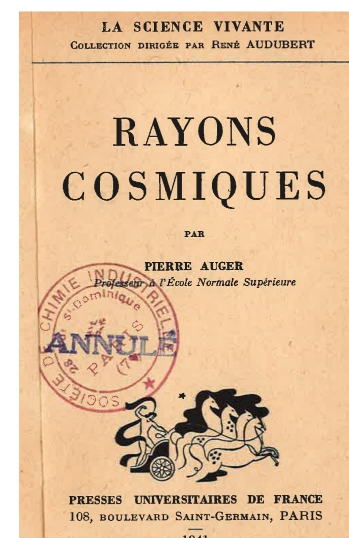
**GZK: $^{A}X + \gamma \rightarrow {}^{A}X + \pi^0$ ($e^+ e^-$)**
few Gpc (z~0.1-0.2) @ 10 EeV
10-100 Mpc (z<0.05) @ 100 EeV

# A >75yrs old mission!



D'ailleurs, quel que soit leur mode de production, pouvons-nous assigner un lieu d'origine aux particules cosmiques ? Si certains corps célestes, certaines

régions du firmament étaient les sources de l'émission des rayons cosmiques, il serait possible de le mettre en évidence par l'étude des variations de l'intensité du rayonnement en fonction de l'heure, solaire ou sidérale. Cela montrerait une dépendance vis-à-vis des constellations et des corps célestes présents au-dessus de l'horizon et surtout près du zénith. Cette étude faite et refaite maintes fois, n'a jusqu'ici montré aucune variation marquée, à part peut-être quelques très faibles modifications diurnes et saisonnières qui peuvent être des effets secondaires dus à des changements atmosphériques. En particulier, la position du soleil, celle de la voie lactée, ne paraissent jouer aucun rôle. Nous pouvons conclure de là que ni le soleil ni des groupes d'étoiles comme la voie lactée ne sont l'origine des rayons cosmiques. Que supposer alors ? viennent-ils des nébuleuses ? des étoiles nouvelles ? des étoiles doubles ? Autant de questions auxquelles nous serons peut-être mieux en état de répondre après avoir poussé plus loin l'investigation sur la nature des rayons cosmiques et sur leurs effets dans la matière. Laissons donc de côté, pour l'instant, cette question n° 1, tout en nous promettant bien d'y revenir plus tard.



# The Pierre Auger Observatory

## Location

West Argentina: 1,400m above sea level
**3,000 km²** (Luxembourg!)

## Components

**Atmosphere**: calorimeter for the shower of daughter particles

**Telescopes:** 'image' showers during dark time (**~10% duty cycle**)

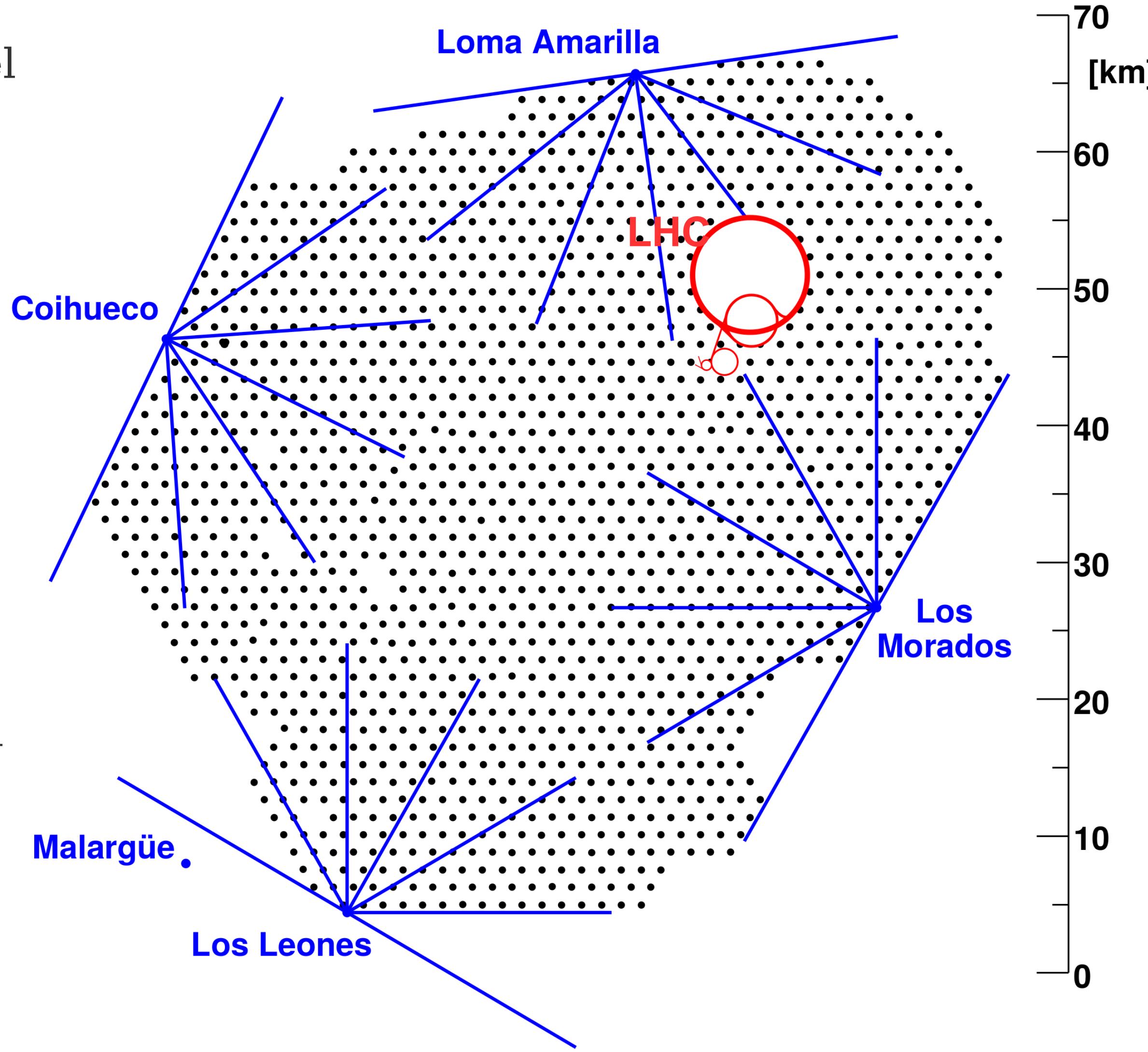
**Particle detectors:** 'collect' μ/e reaching ground (**~100% duty cycle**)

## Fluorescence Telescopes

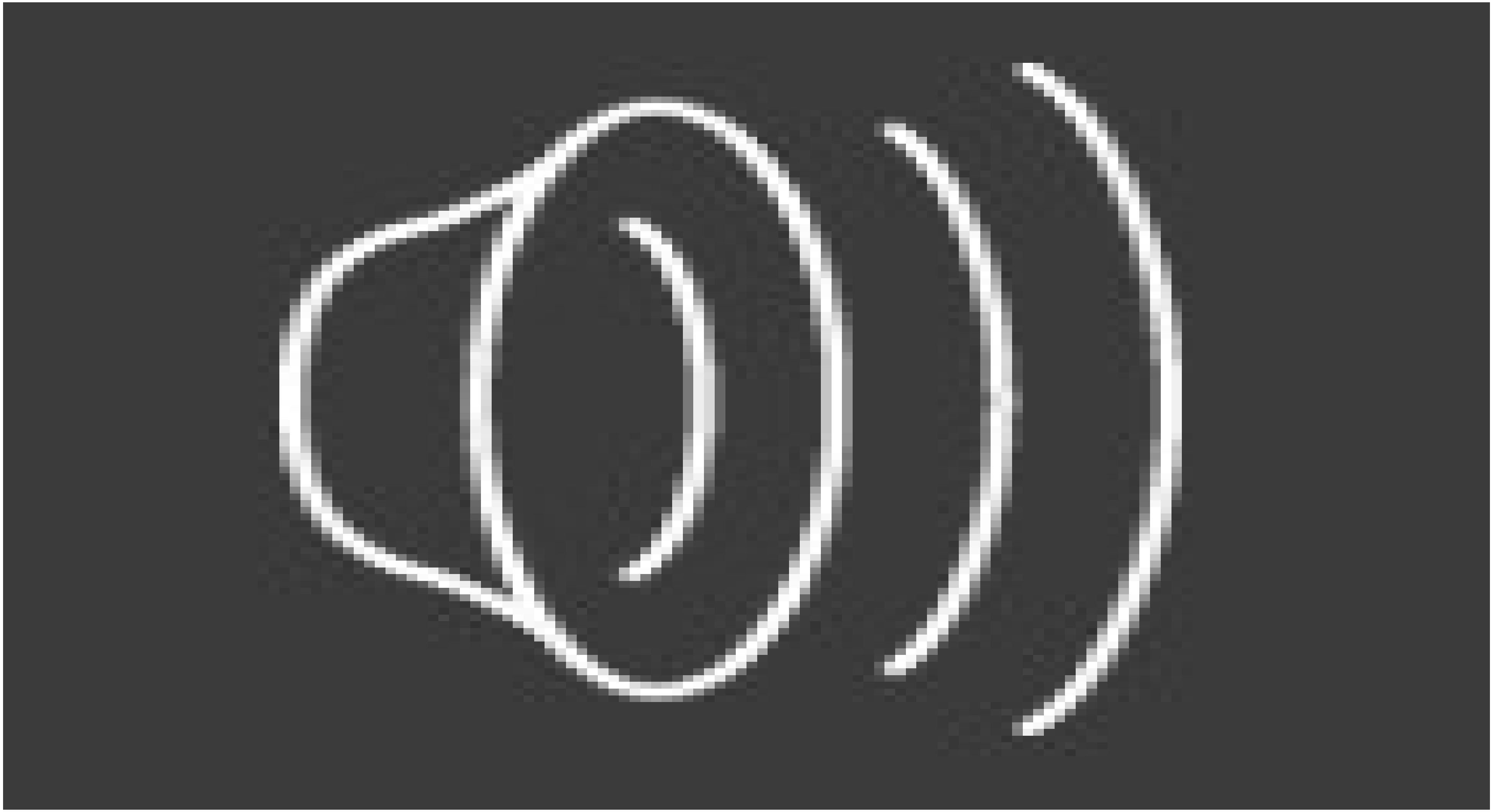
27 fixed cameras (PMTs) in 5 buildings
4 main sites: 6 eyes/site – 30°×30° FoV

## Particle Detectors

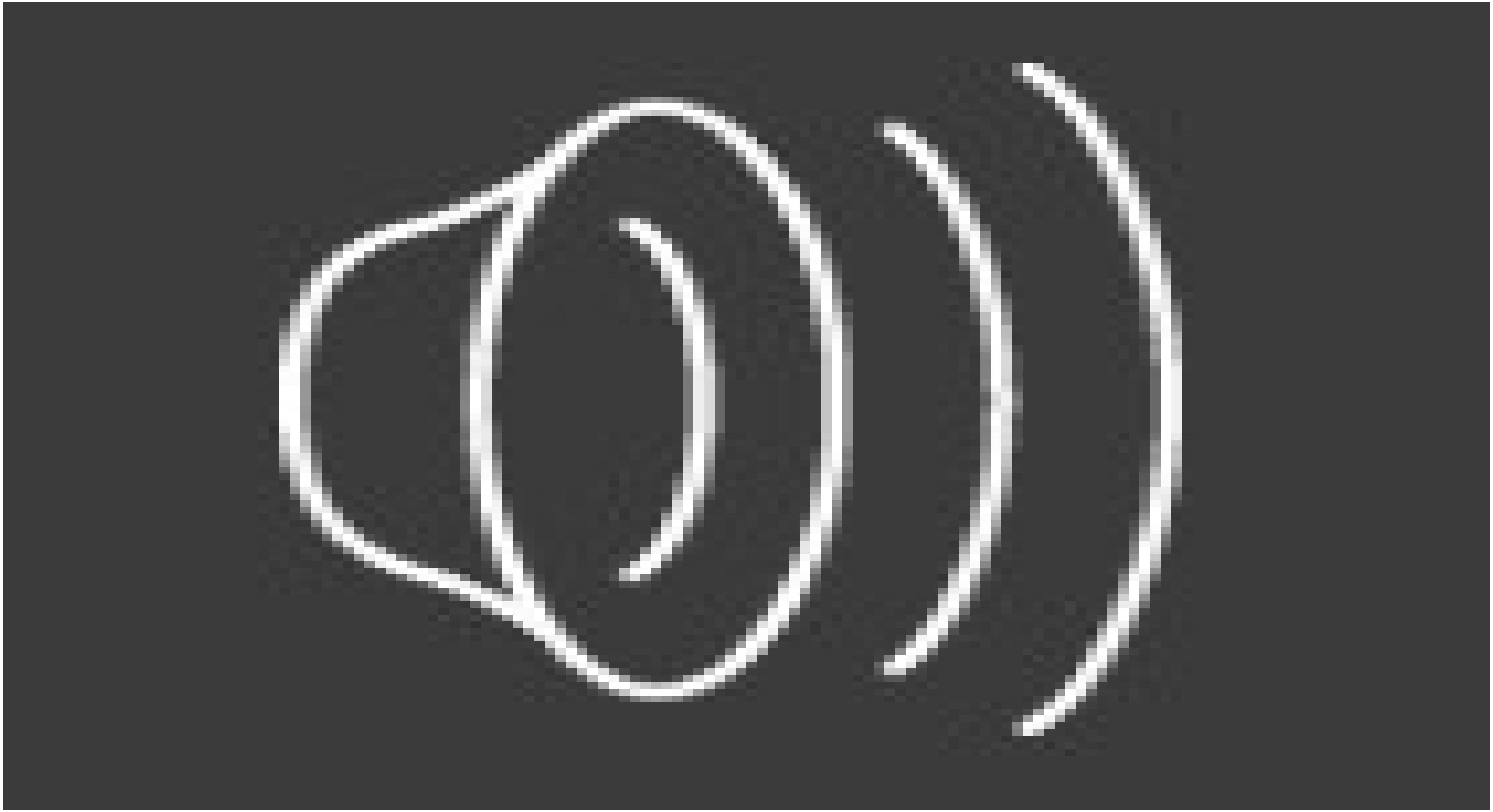
1600 water-Cherenkov tanks
3 PMTs per tank, spaced by 1,500m
(+infill: 50 spaced by 750m)



# Surface array – collecting daughter particles



# Surface array – collecting daughter particles

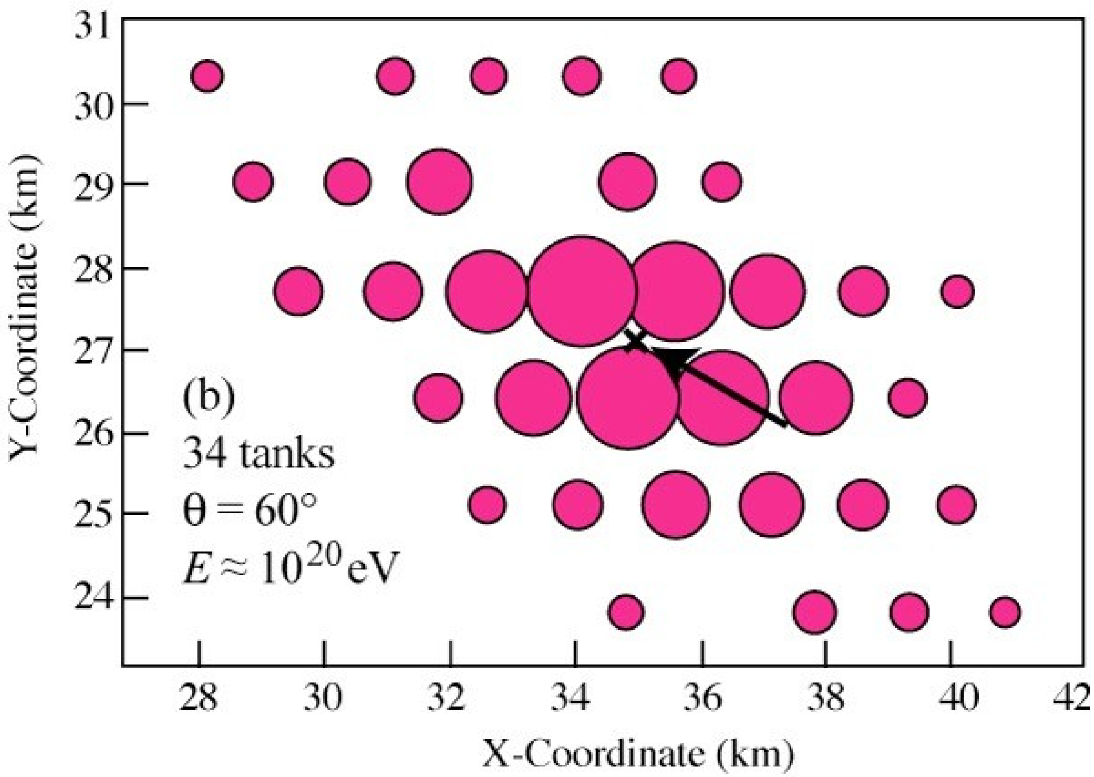


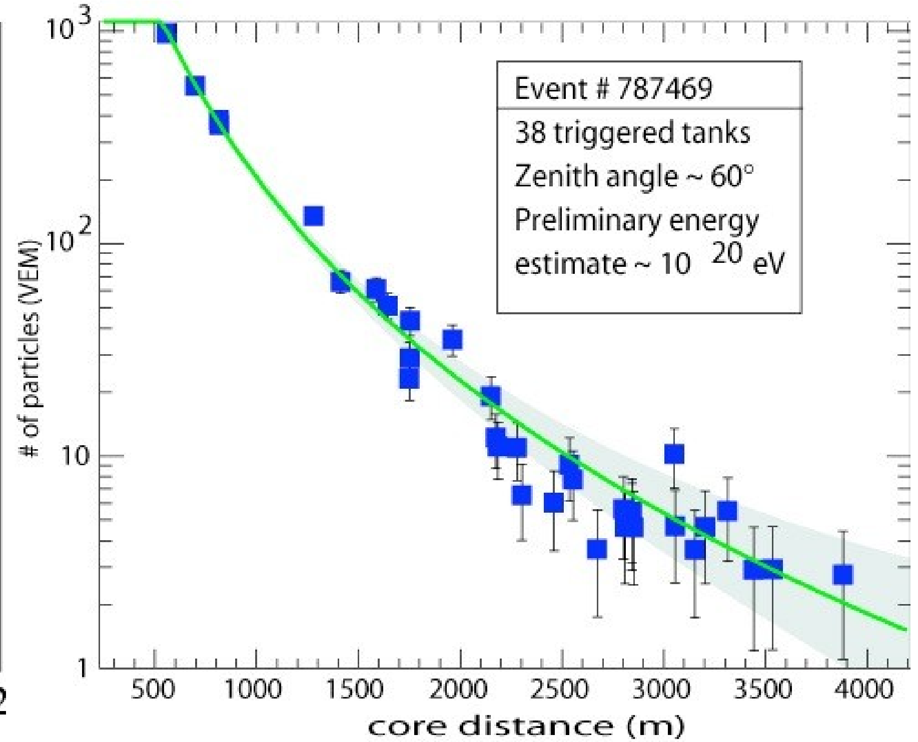
# Surface array - performance

## Detection of an UHECR event

Trigger of a 'hot' station and its neighboring tanks → 25ns-sampled signal from the array

Array status monitored every minute → number of active detection 'cells' → exposure




## Reconstruction of an UHECR event

**Charge** vs distance → **energy estimator** / **Timing** vs distance → **direction estimator**

Energy estimator calibrated against fluorescence measurements for 'golden-hybrid' subset

# High-level products

## Event rate vs energy → spectrum

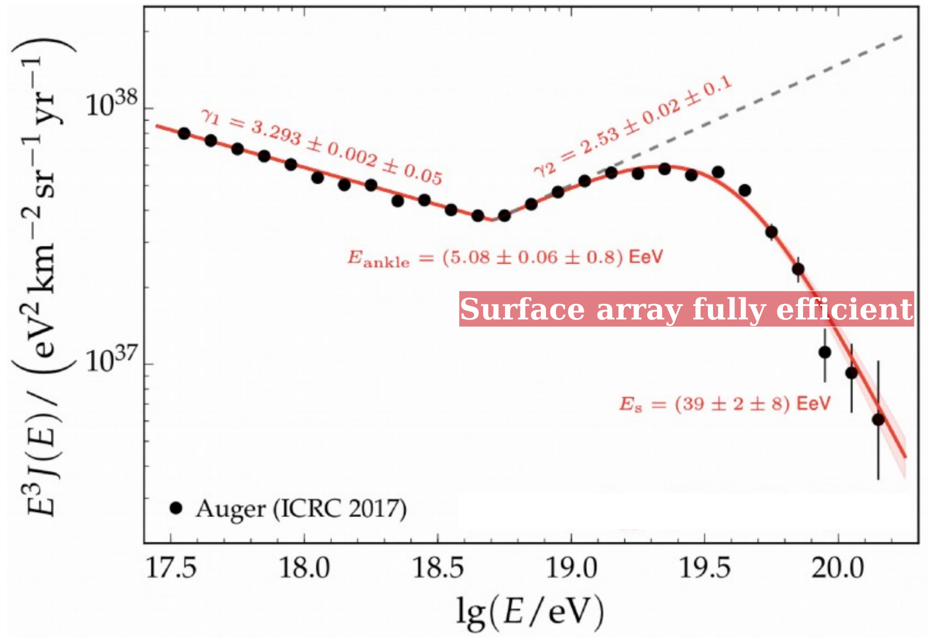
Energy resolution / event: **<12%** above 10 EeV

*vs <20% >0.1 TeV for γ-rays (H.E.S.S.)*
*vs <10% >0.1 PeV for contained ν (IceCube)*

Systematic on the energy scale (fluo): **~14%**

Surface array **fully efficient > 4 EeV**

Combining infill (low E), hybrid events (mid E), surface array (high E) → **overall spectrum**



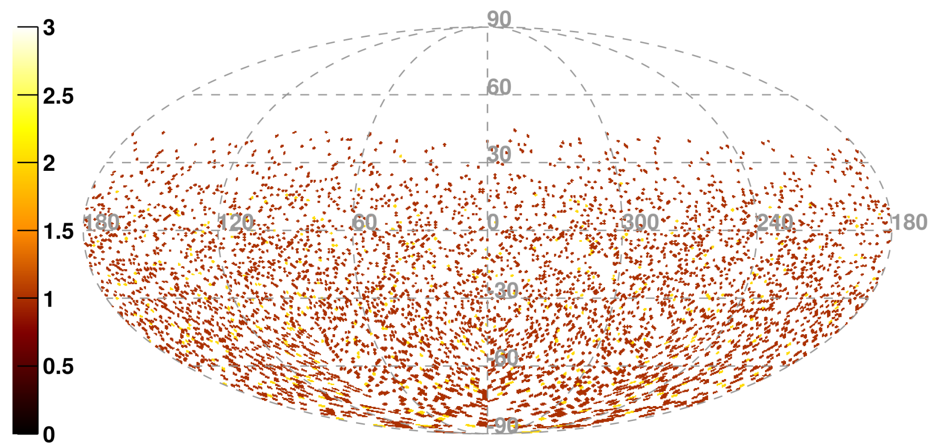

## Event rate vs direction → anisotropies

Angular resolution / event: **<0.9°** >10 EeV

*vs <0.1° >0.1 TeV for γ-rays (HESS)*
*vs ~15° > 0.1 PeV for cascade-like ν (IceCube)*

Combining vertical (zenith angle <60° )
and inclined events (60-80°) → **85% coverage**

Event Map - Equatorial coordinates (R.A. / Dec)




## Compo. barely addressed in this talk

Mostly probed through Xmax (fluorescence)

+ surface: time profiles!

Pierre Auger Coll. 17

## Large-scale Anisotropy
## A discovery

The Pierre Auger Collaboration, Science 357 (2017)

RESEARCH ARTICLE

COSMIC RAYS

**Observation of a large-scale anisotropy in the arrival directions of cosmic rays above $8 \times 10^{18}$ eV**

The Pierre Auger Collaboration*†

# Rayleigh Analysis in Right Ascension

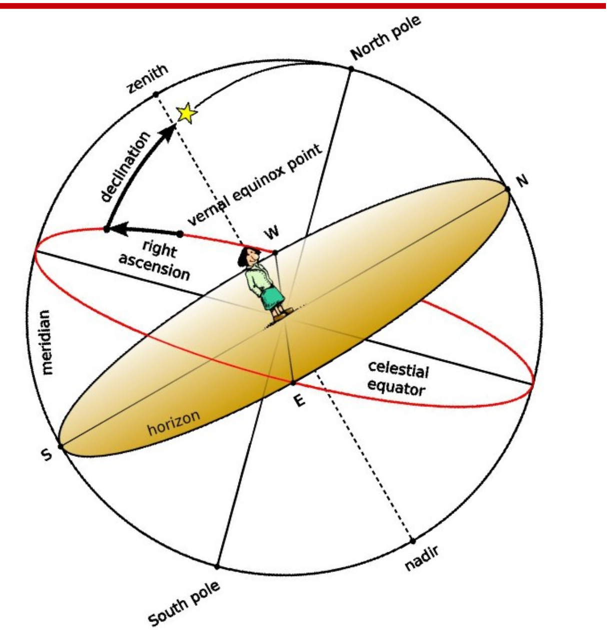
## Equatorial coordinate system

Spherical coordinates with z along Earth's rotation axis

→ Right Ascension. ($\alpha \equiv \Phi$), Declination ($\delta \equiv \pi/2 - \theta$)

**Directional exposure constant in R.A.**

. Sidereal day (vernal to vernal eq.): 23h 56m 4s
. Diurnal/nocturnal variations: 24h
→ solar / sidereal frequency: control of accuracy




## Rayleigh analysis in R.A.

Pierre Auger Collab. 2012

$$a_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos \alpha_i$$

$$b_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin \alpha_i$$

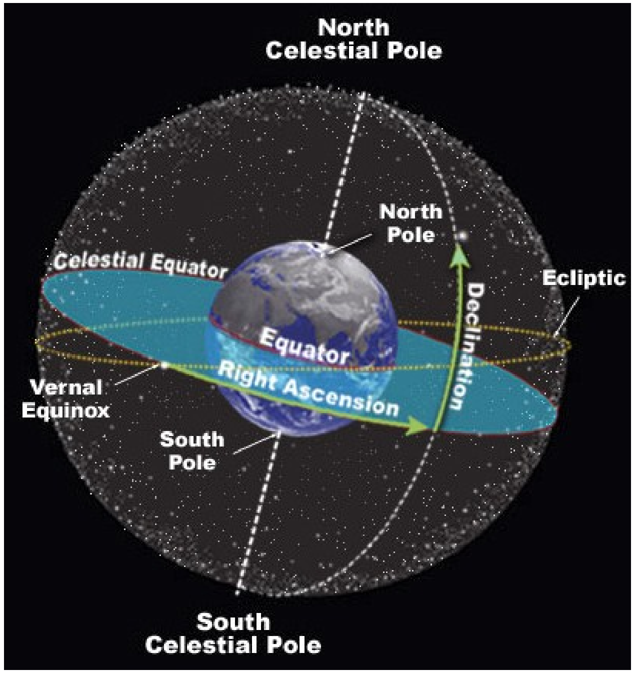
→

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

$$\tan\varphi_\alpha = \frac{b_\alpha}{a_\alpha}$$

$\alpha_i$: R.A. of the event, $w_i$=array non-uniformity / tilt ($\mathcal{N}=\Sigma w_i$)

**→ r, φ: amplitude, phase of the 1st harmonic in R.A.**




## Deviation from isotropy

Linsley 1975

$$P(r_\alpha) = \exp(-\mathcal{N} r_\alpha^2/4)$$ → **p-value** for a single tested dataset

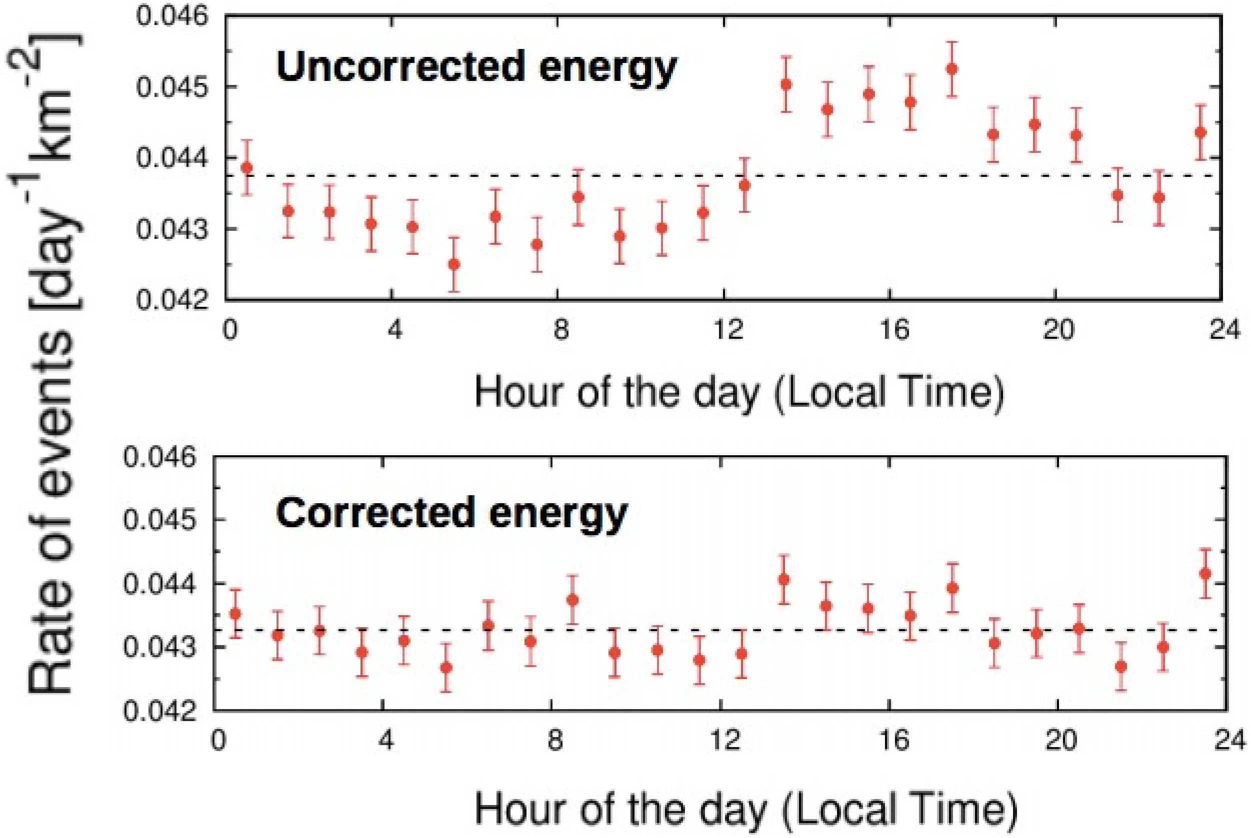
# Control of the array

## Energy corrections

. Air density → lateral distribution of the electromagnetic component of the shower

. Pressure → longitudinal depth of observation

→ modulations in ±1.7% in solar frequency: corrected for: only stat. fluke remain



# Rayleigh analysis in Right Ascension

## Study in two energy bins

Array fully efficient up to 80° > 4 EeV

**4-8 EeV**: ~82,000 events

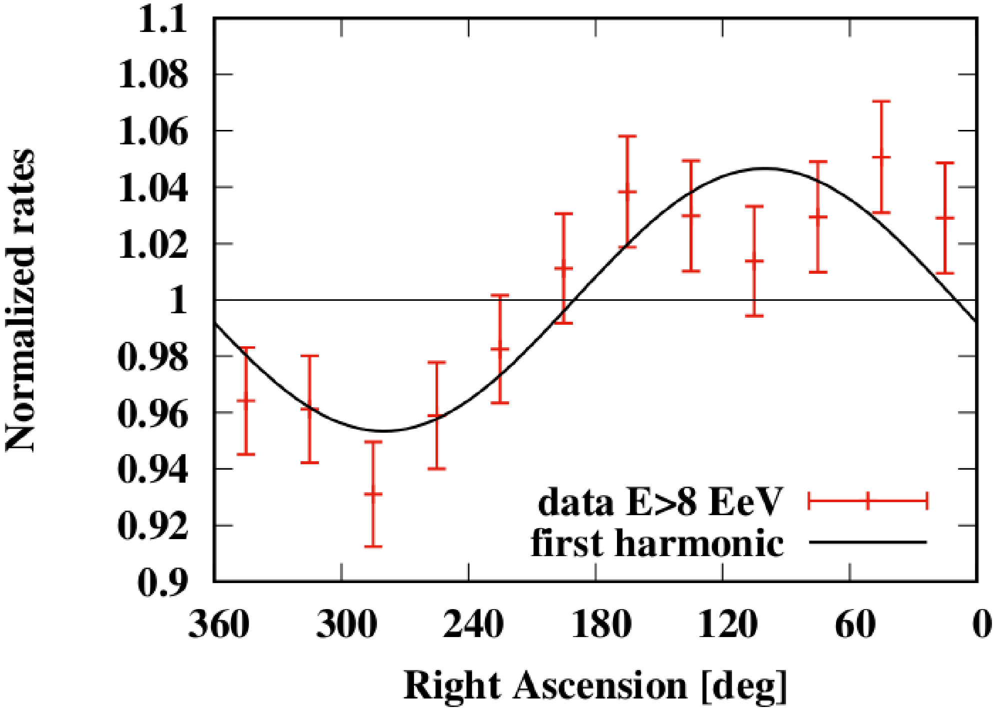
φ = 80±60°, r < 1.2% (95% C.L.)

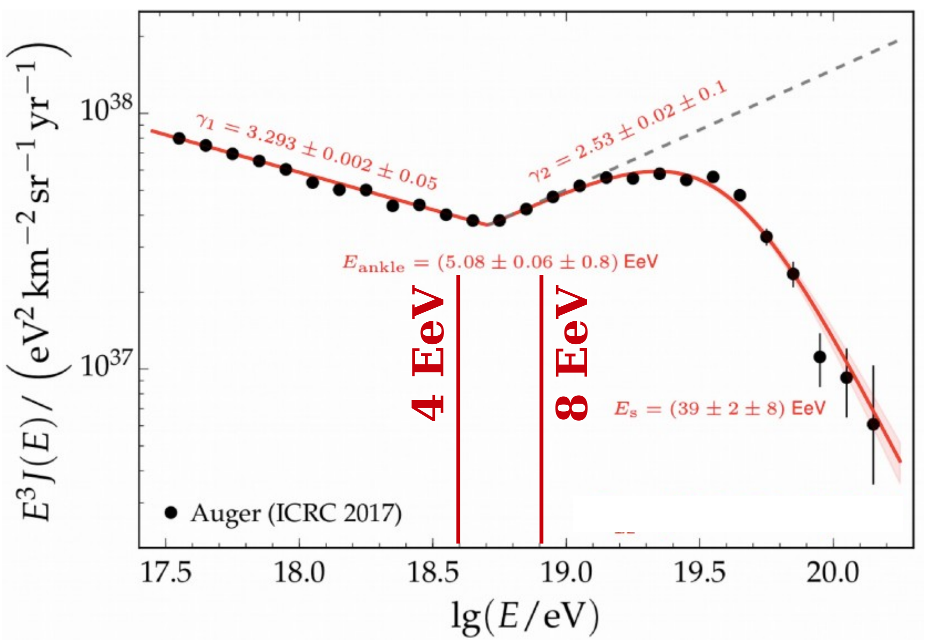
→ no significant modulation

**>8 EeV**: ~32,000 events

φ = 100±10°, r = 4.7%±0.8%

→ **local p=2.6 × $10^{-8}$!**




## Penalization for the energy scan

Study in 2 independent energy bins

→ global p-value of 5 × $10^{-8}$

→ first harmonic significant at the **5.4σ level**

# Recontructing the dipole in the sky

## Main assumption

Development over spherical harmonics up to 1$^{st}$ order

→ monopole (isotropic component) + dipole

→ R.A. analysis provides dipole component ⊥ Earth's axis

## Reconstruction in azimuth

Geomagnetic field break shower circular symmetry
→ azimuth modulation ~0.7% corrected for in energy

Azimuthal component → projection along Earth's axis

Provided latitude of the observatory, and the average declination (δ) and zenith (θ) of the events:

**Dipole amplitude**

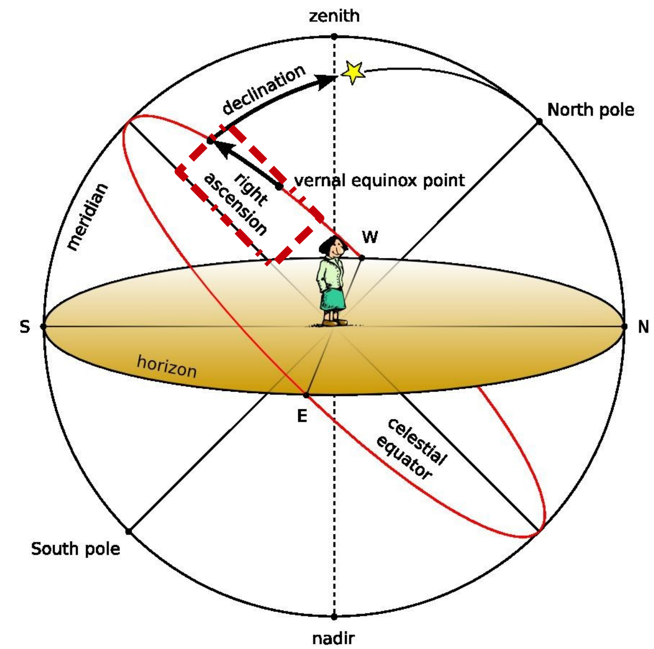
$$d_\perp \approx \frac{r_\alpha}{\langle \cos \delta \rangle}$$

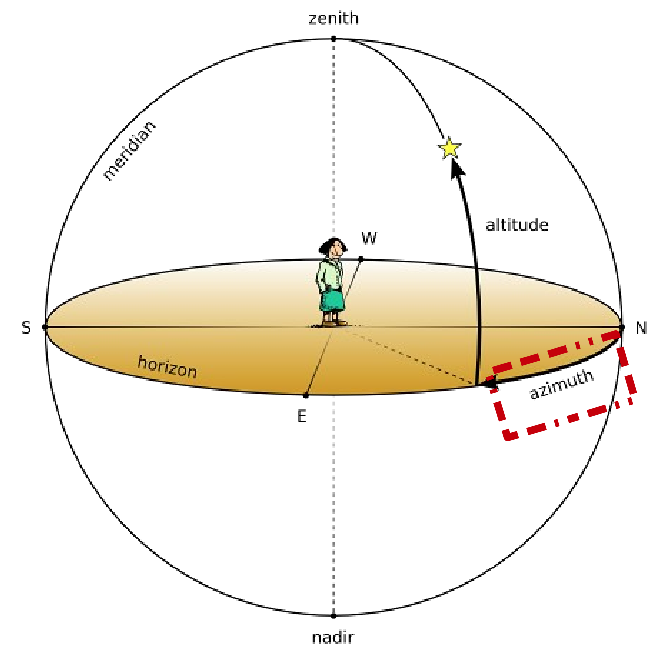
$$d_z \approx \frac{b_\varphi}{\cos \ell_{\mathrm{obs}} \langle \sin \theta \rangle}$$

**Dipole direction**

$$\alpha_d = \varphi_\alpha$$

$$\tan \delta_d = \frac{d_z}{d_\perp}$$

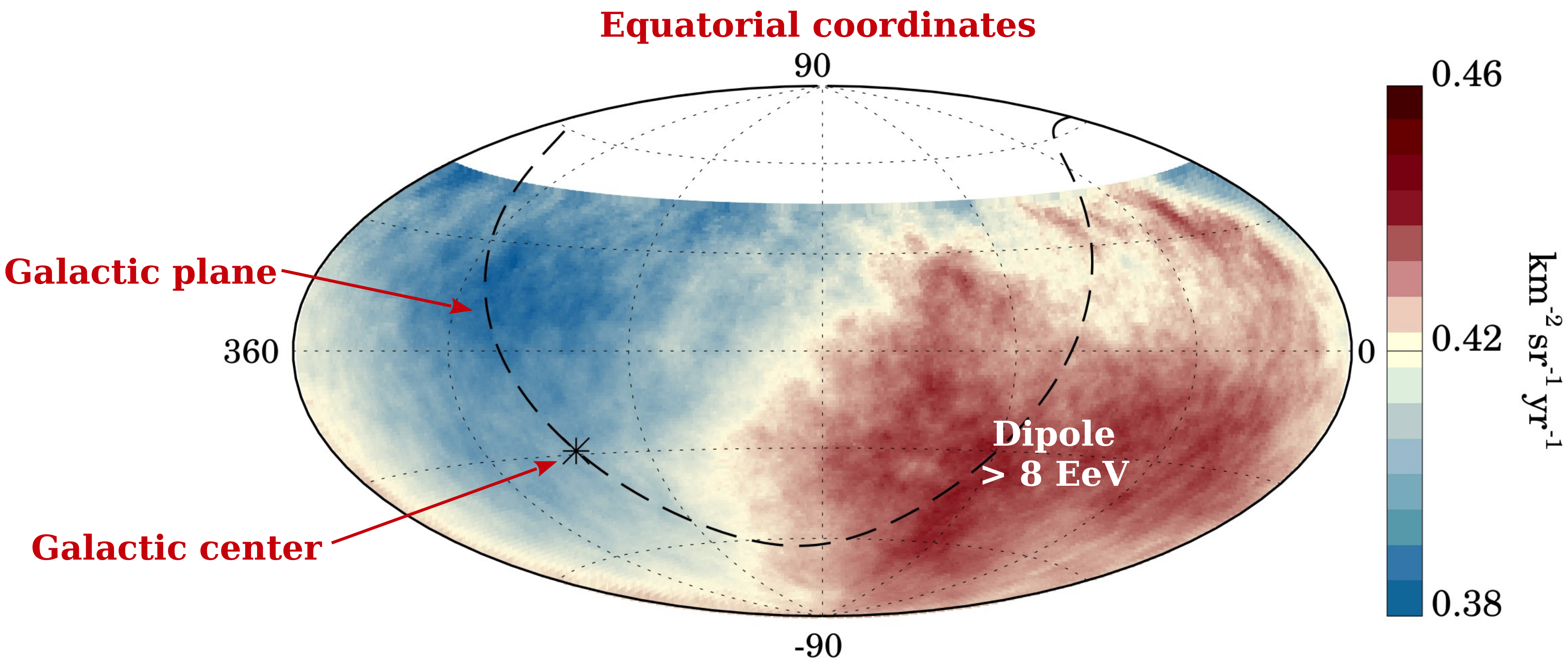


# Combining Right Ascension and Azimuthal

## Amplitude of the dipole > 8 EeV

d = 6.5%±1.0% → max at +7%, min at -7% / 1 half of the sky +7% brighter than the other




## Direction of the dipole > 8 EeV

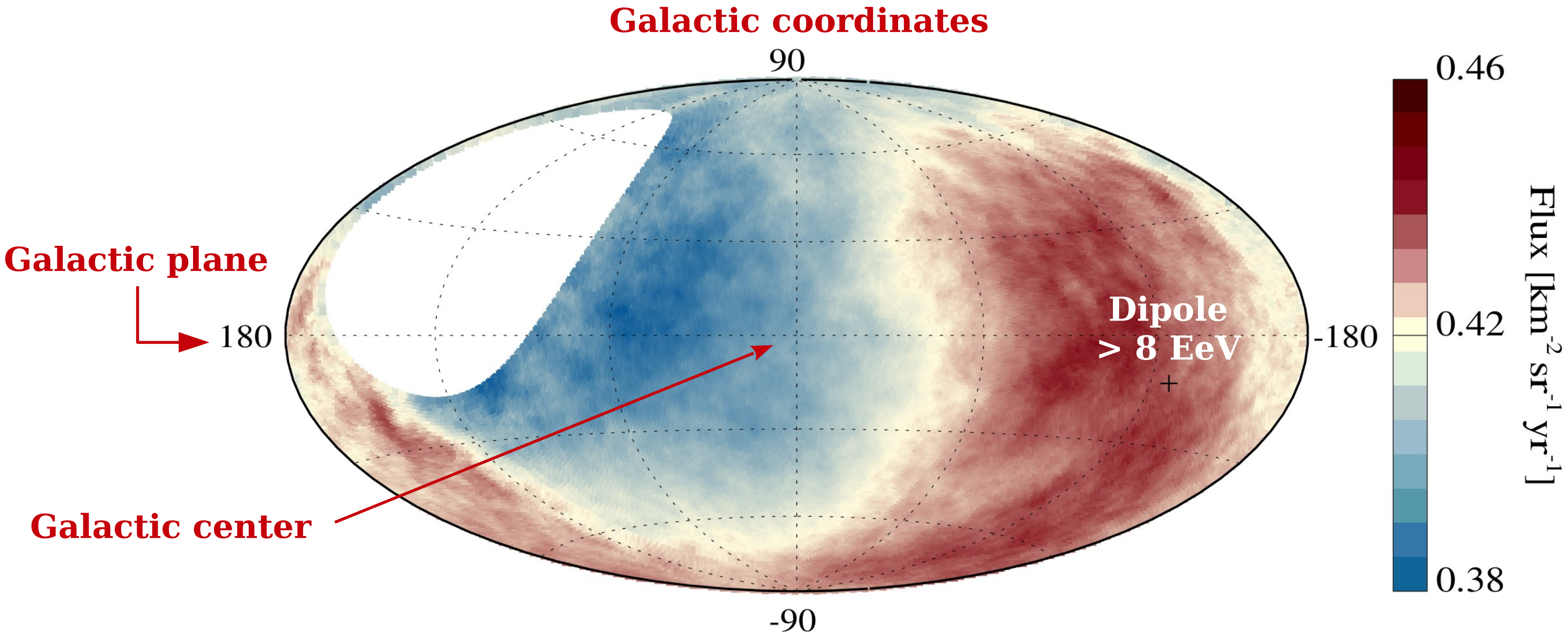
Right ascension α =100±10°, Declination δ = -24±13°

# A Dipole in the UHECR sky

## Amplitude of the dipole

d = 6.5%±1.0% → 10× larger than from proper motion wrt large scale structures!

**→ astrophysical sources with anisotropic flux distribution?**




## Direction of the dipole

125° ± 12° from the Galactic center → hard to reconcile with Galactic origin, unless quite peculiar structure of the Galactic magnetic field (center = sink → anti-center? Eichler+16)

# Where are other galaxies pointing to?

## Dipoles in the sky

Investigated in EMAG bands: search for deviations from homogeneity (cosmological principle)

High-z: should point to CMB dipole

## 2MASS redshift survey

45k galaxies observed in IR

Densest sampled all-sky survey with spectroscopic redshifts

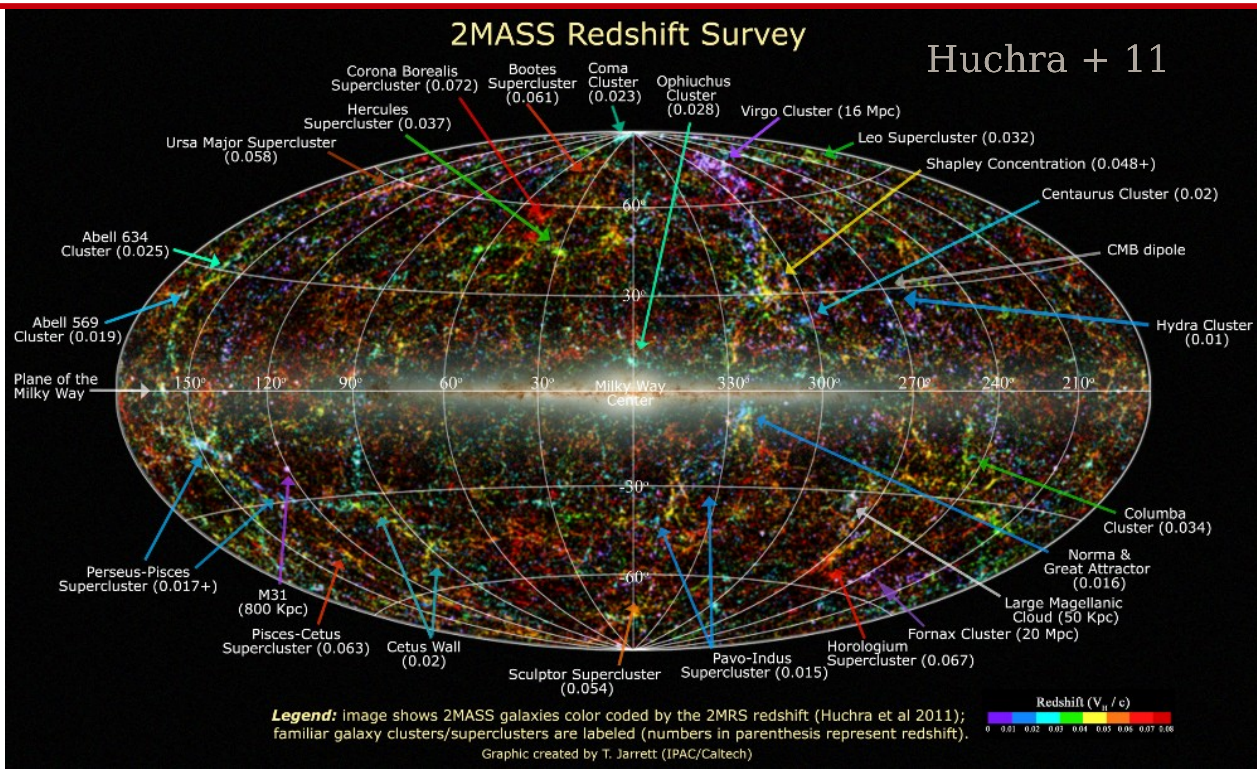
Galaxies on average at 100 Mpc, up to ~300 Mpc

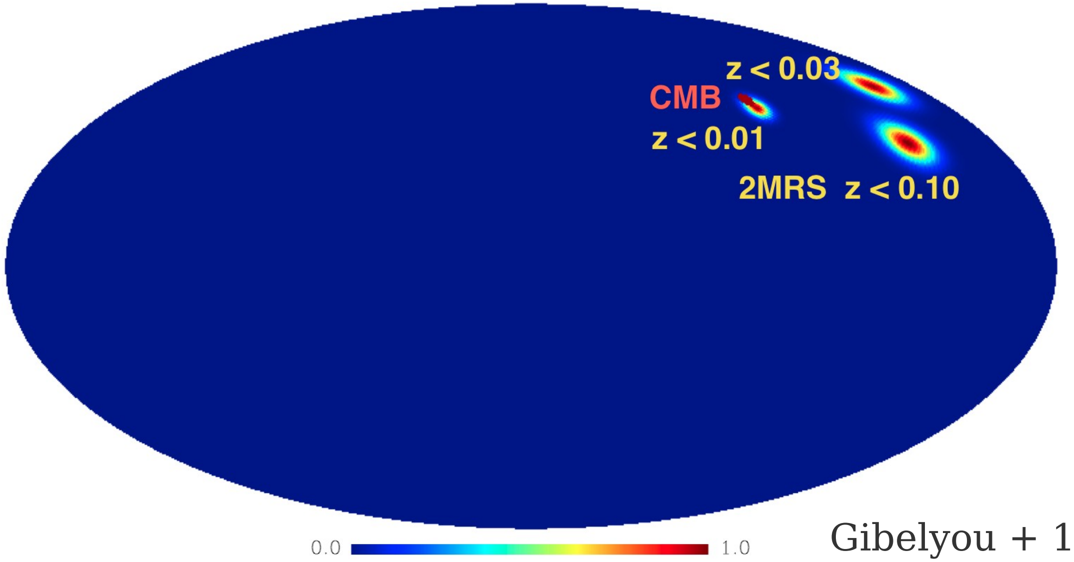
## 2MRS dipole

Exclude Local Group (Andromeda, Triangulum, satellites)

Dipole in flux/number (12±1%) about 20°away from CMB

Erdogdu+ 06, Gibelyou + 12



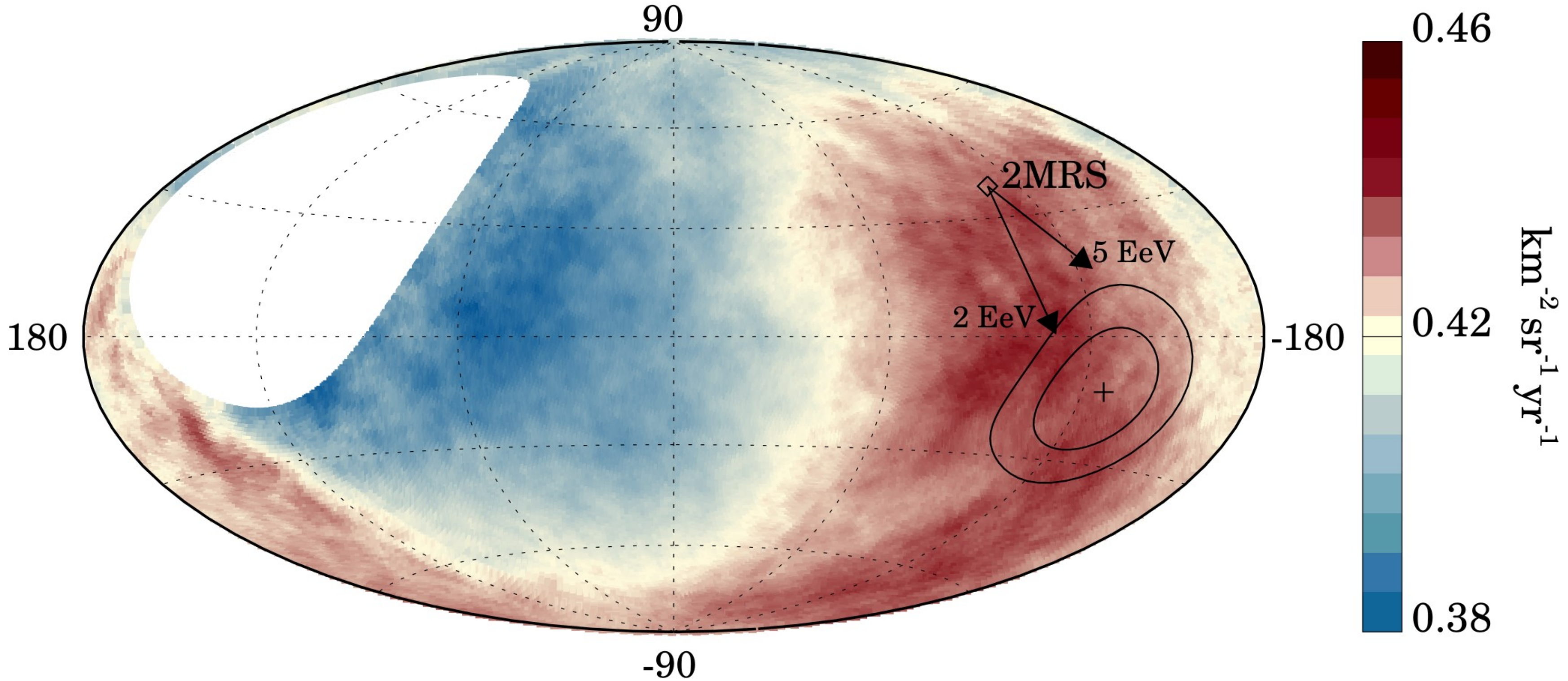

Gibelyou + 12

# UHECR & 2MRS dipoles

## Effect of Galactic magnetic field (GMF)

Deflections in GMF: a few 10° Z (E / 10 EeV)$^{-1}$, with <Z>~2-5 at ~10 EeV (fluorescence)

Test realizations: use the GMF model of Jansson & Farrar 12 → **good direction!**




## Conclusion

First detection >5σ of a large-scale anisotropy > 8 EeV

Direction & amplitude consistent with an extragalactic origin → **All / which galaxies???**

# Which galaxies?
# An indication

The Astrophysical Journal Letters, 00:000000 (9pp), 2018 Month Day


CrossMark

**An Indication of Anisotropy in Arrival Directions of Ultra-high-energy Cosmic Rays through Comparison to the Flux Pattern of Extragalactic Gamma-Ray Sources**

The Pierre Auger Collaboration, accepted in ApJL (2018)

# A multimessenger approach

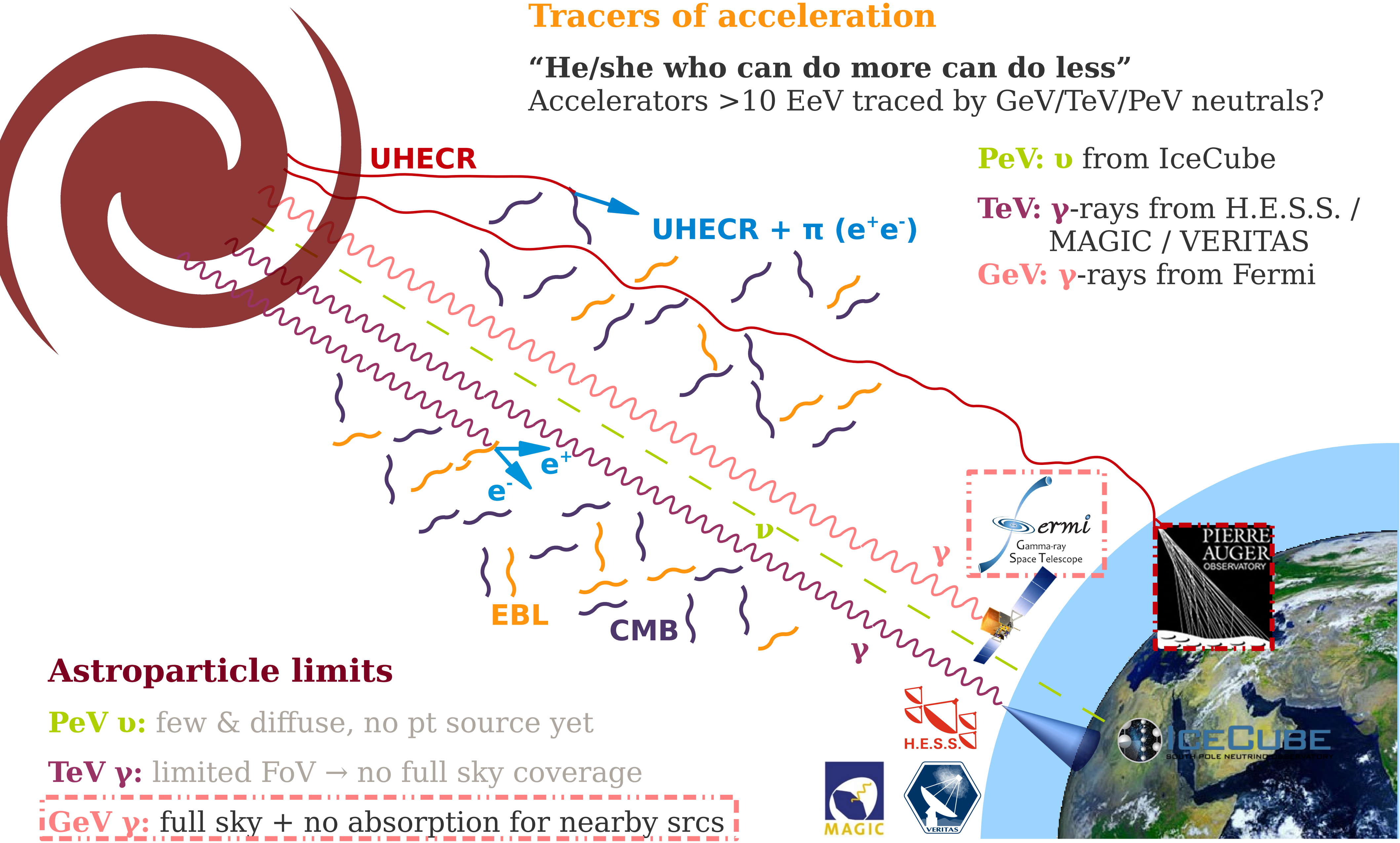
## Tracers of acceleration

**“He/she who can do more can do less”**
Accelerators >10 EeV traced by GeV/TeV/PeV neutrals?

**PeV: υ** from IceCube

**TeV: γ**-rays from H.E.S.S. / MAGIC / VERITAS

**GeV: γ**-rays from Fermi




## Astroparticle limits

**PeV υ:** few & diffuse, no pt source yet

**TeV γ:** limited FoV → no full sky coverage

**GeV γ:** full sky + no absorption for nearby srcs

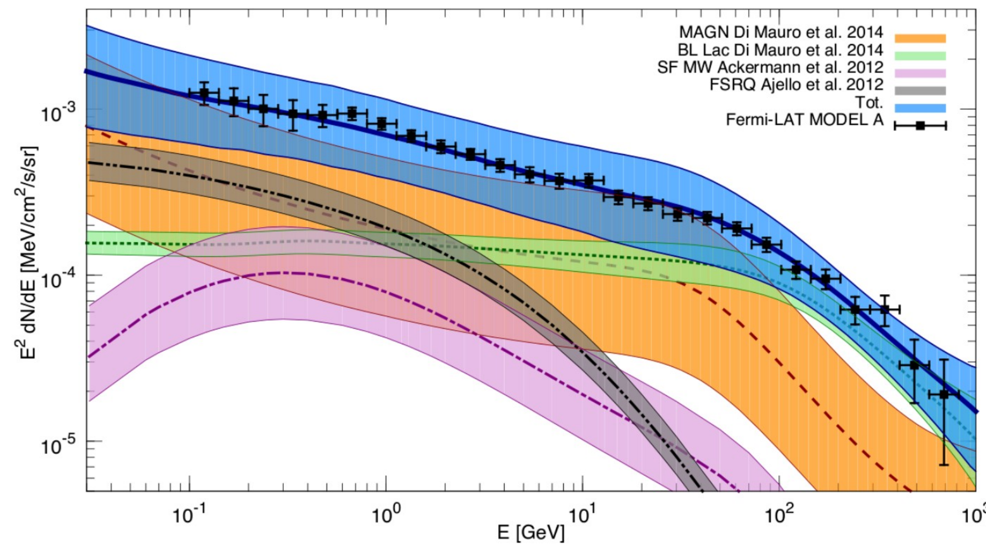
# Lessons learned from gamma rays

## Extragalactic γ-ray background

Two types of sources dominating the GeV resolved and unresolved extragalactic sky:

- **Active galaxies** (AGN)
  *Radio galaxies* + *Blazars* (*BL Lacs* / *FSRQs*)
- Star-forming galaxies, **starburst galaxies**

Extragalactic γ-ray Background, Di Mauro+ 15

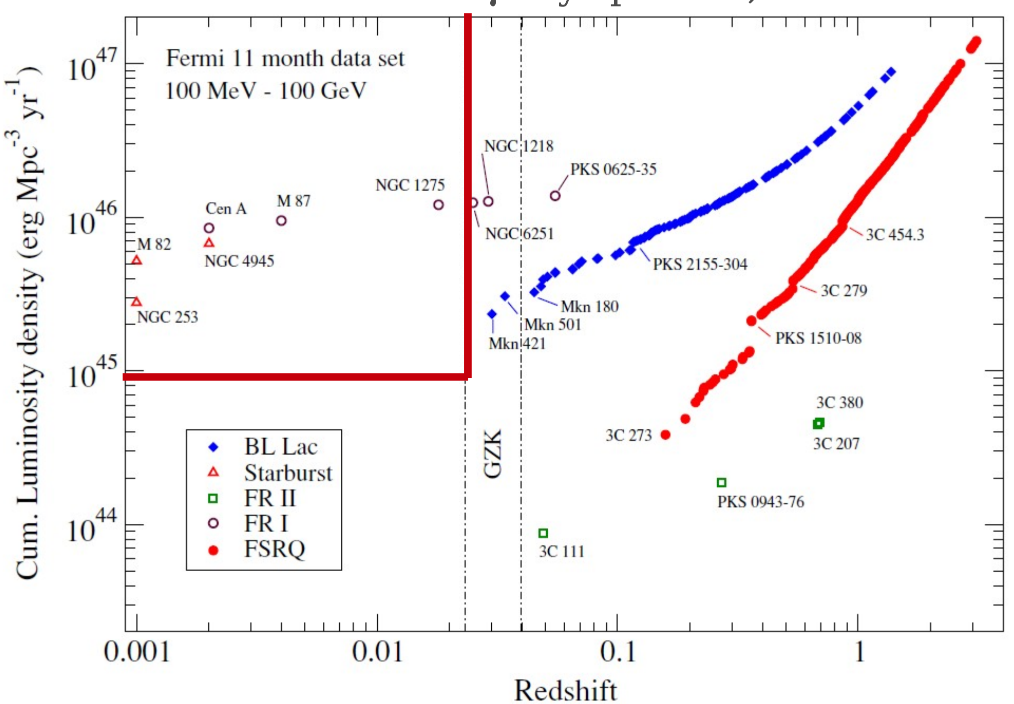



## Requirement on UHECR power

Rate of energy production for UHECR > 1 EeV: ~ $10^{45}$ erg $Mpc^{-3}$ $yr^{-1}$ Unger +15

→ **both starbursts & AGN match this limit if L(UHECR) ~ 10% L(γ)**

Cumulated γ-ray "power", Dermer+ 10




## Extragalactic TeV sources

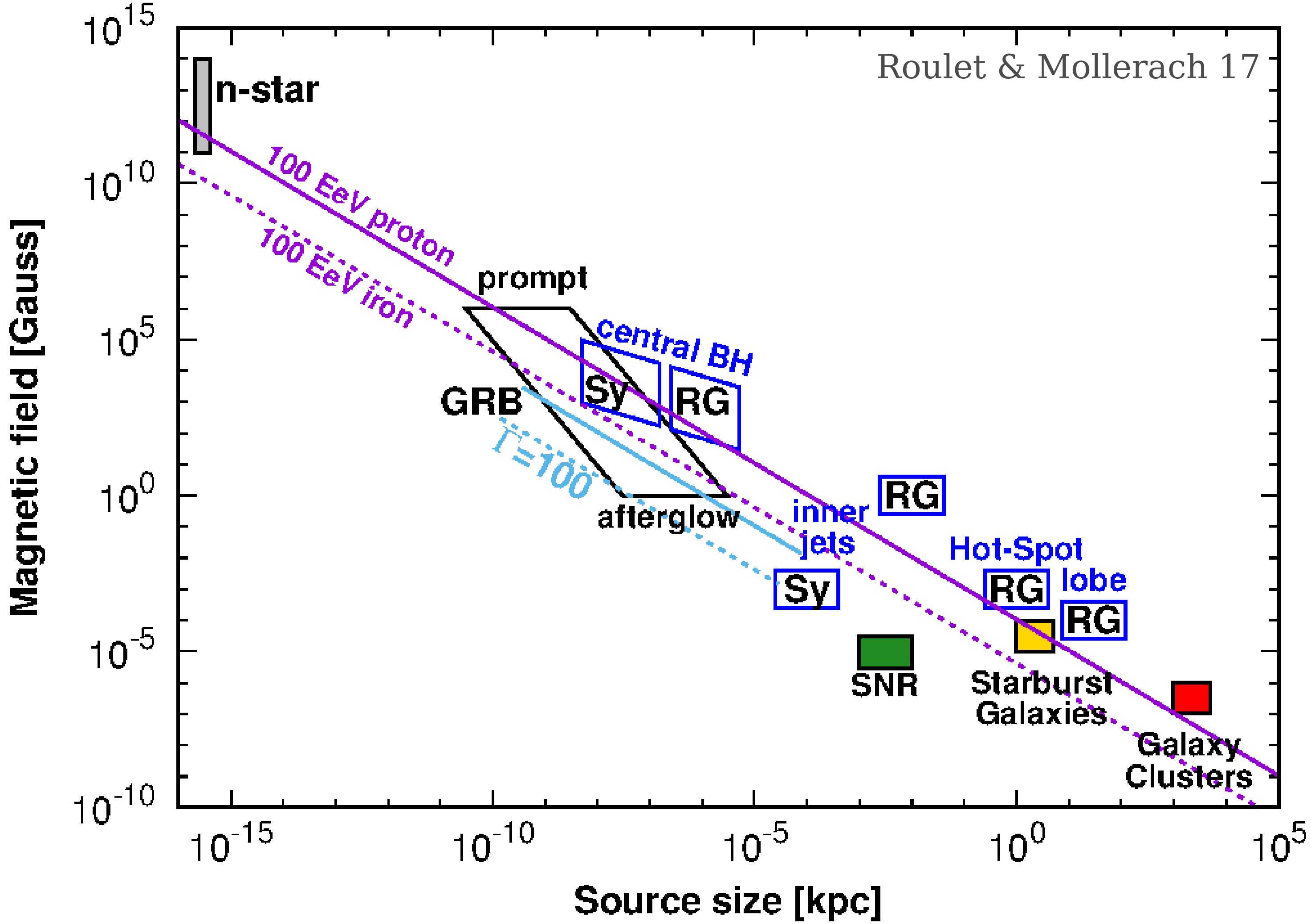
Active galaxies (mostly blazars)
+ 2 starburst galaxies (NGC 253 & M82)

# Does it work? Hillas criterion

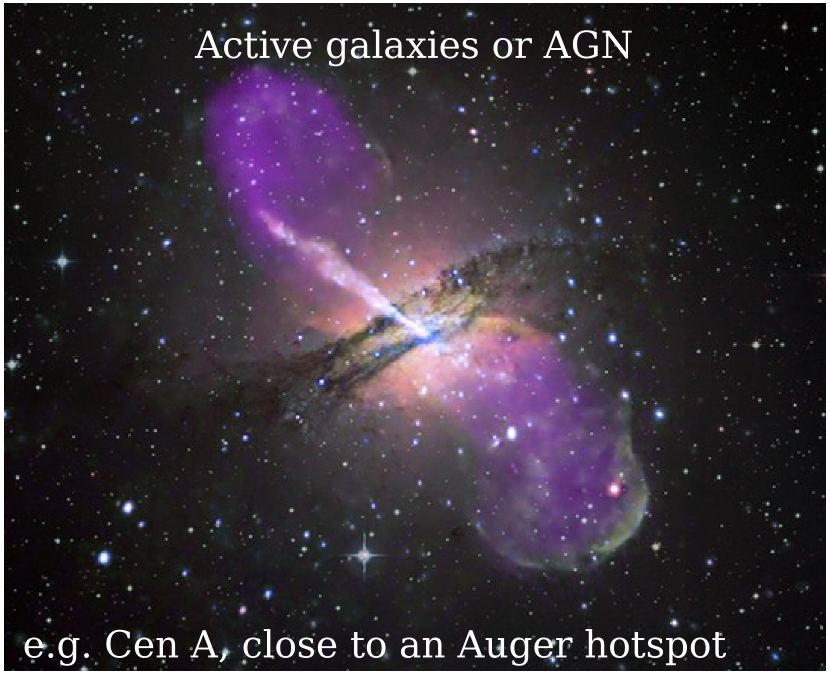
## Classical test an UHECR candidate should pass

Keep the particle confined in a region of size R with a B-field until acceleration up to $E_{max}$

Larmor radius (E'/ZeBc) in source frame (/Γ) < R → $\mathbf{E_{max}}$ **=** (ZΓec) × **B × R > ~100 EeV**

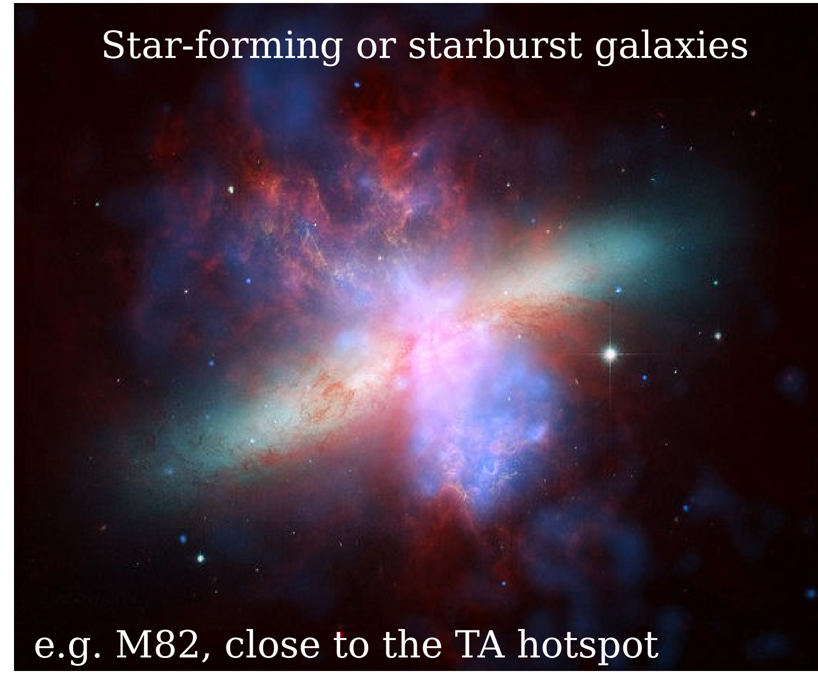


# AGNs and SBGs in our vicinity




AGNs from the 2FHL Catalog
(*Fermi*-LAT, > 50 GeV)
within 250 Mpc

Ackermann+ 16




'Starbursts' from *Fermi*-LAT search list
(HCN survey) within 250 Mpc
with radio flux > 0.3 Jy

Gao & Salomon 05

**Assumption: UHECR flux ∝ non-thermal photon flux**

*Note: inspired from Pierre Auger Collaboration 2011*
*but differs from most past UHECR studies:*
*doesn't assume that sources are 'standard' candles*

# Effect of attenuation / composition

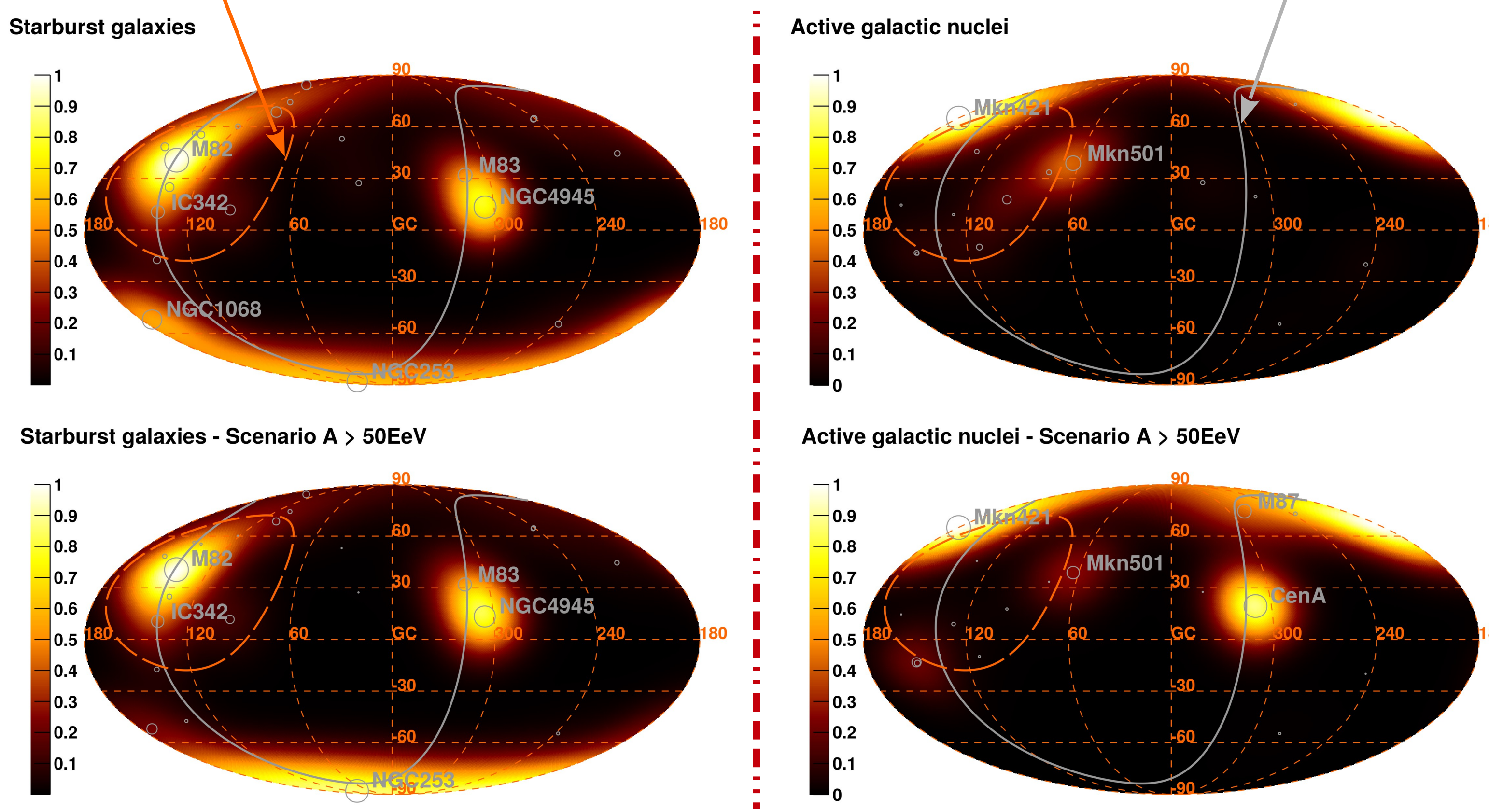
Limit of Auger FoV

Supergalactic plane

Galactic coordinates

No attenuation

Attenuation (A)




## Three data-driven composition scenarios tested

Pierre Auger Collab. 2017

**Starburst galaxies**: nearby (90% of flux < 10 Mpc) → attenuation/none: **small impact**

**Active galaxies**: more distant (90% of flux < 100 Mpc) → attenuation/none: **impact!**

# Analysis: maximum likelihood ratio test

## Extracting the signal

Test arrival directions of UHECR vs **density maps** → unbinned max likelihod (à la Fermi)

*Note: again differs from UHECR studies based on cross correlation – 1 source ≠ 1 weight*

**Null: Isotropy**

$L(-,0) = \prod_{events} \text{exposure}(\mathbf{n}_i)$

*with ∫ dΩ exposure(Ω) = 1*

**Alternative: Source contribution**

$L(\theta,\alpha) = \prod_{events} [\text{exposure} \times \textbf{model}(\theta,\alpha)](\mathbf{n}_i)$

α: signal fraction (anisotropic)
θ: search radius

*with ∫ dΩ [exposure×model](Ω) = 1*

**model**: [α×density + (1-α)×isotropic] ⊗ Fisher(θ)

*Fisher(θ) ~ Gaussian(θ) on the 2D sphere*

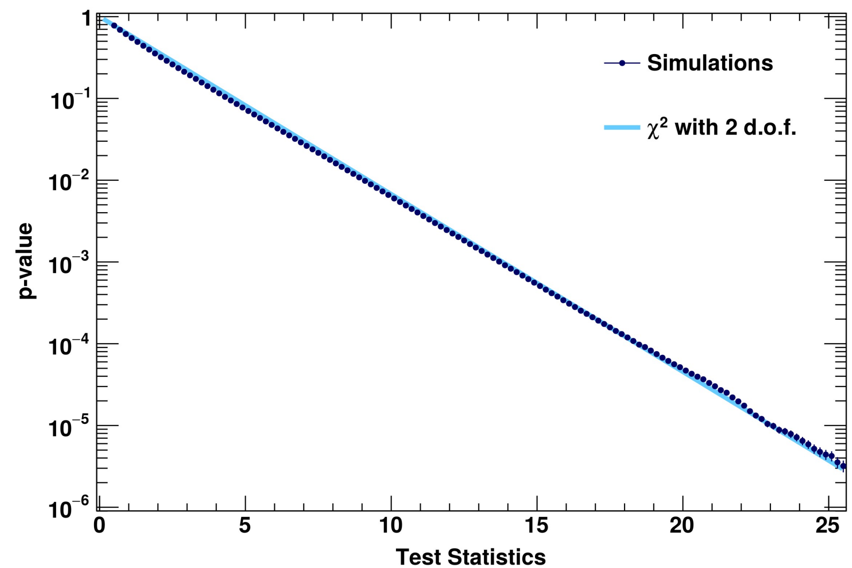
## Test statistics and local p-value

$TS = 2 \log[\, L(\theta,\alpha) / L(-,0)\, ]$

TS is $\chi^2$ distributed with 2 d.o.f. (θ, α)
*α=0 → Alternative = Null → Wilks' theorem*

## Energy scan and global p-value

Scan over threshold energy as in past Auger works
→ MC-based penalization - factor ~O(10)



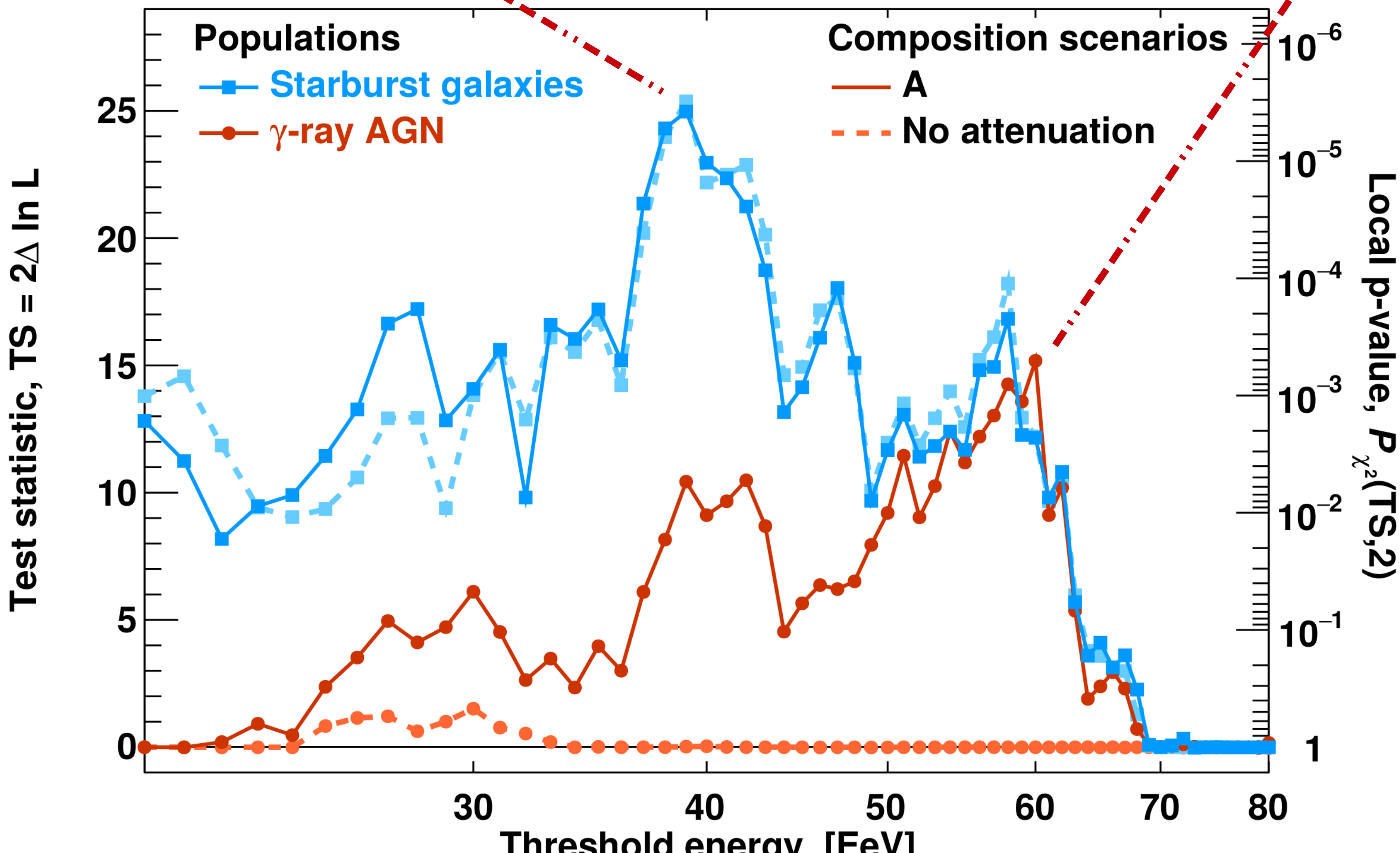
# Result of the scan: the starburst indication!

## Starburst galaxies

E > 39 EeV: **N = 894 events, TS=24.9**
α=9.7%, θ=12.9° → local p-value: $3.8 \times 10^{-6}$
$E_{th}$ → global p-value: $3.6 \times 10^{-5}$ → **4.0σ**

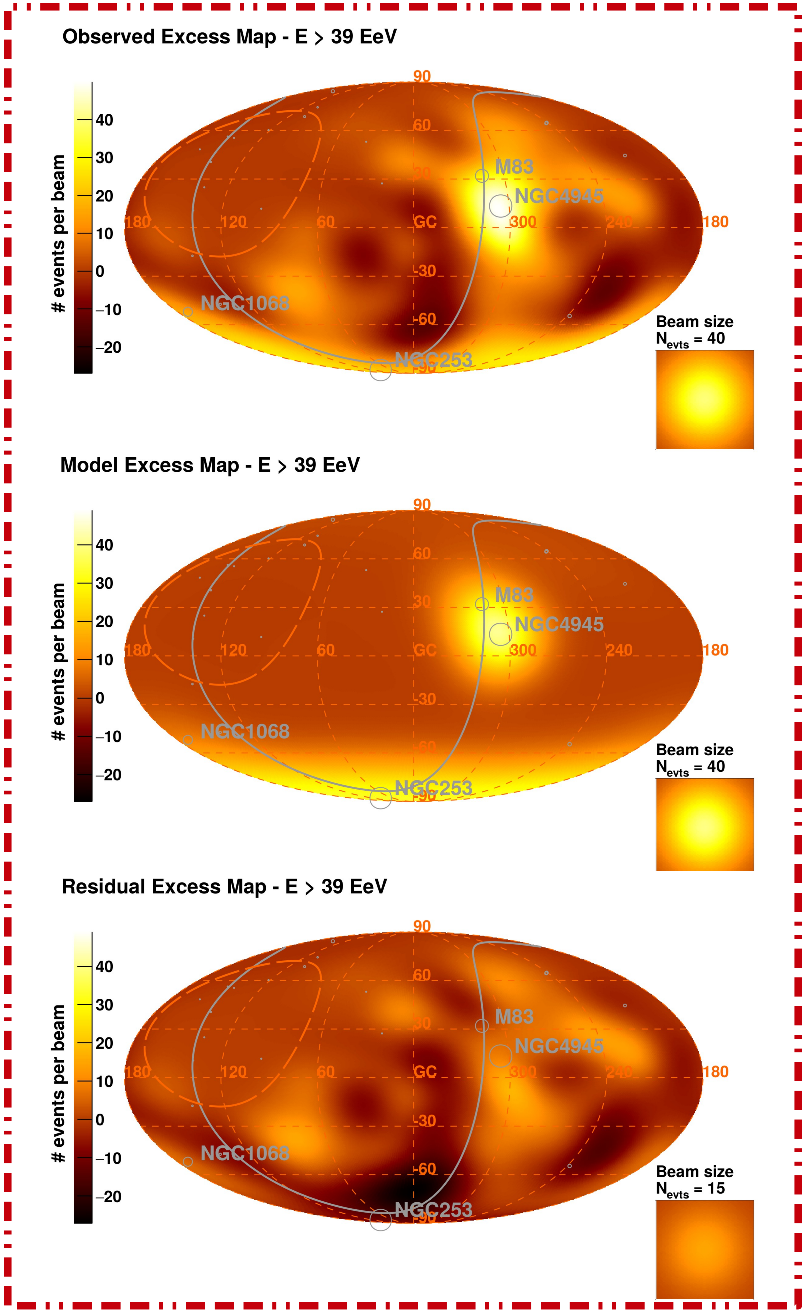
## Active galaxies

E > 60 EeV: **N= 177 events, TS=15.2**
α=6.7%, θ=6.9°→ local p-value: $5.1 \times 10^{-4}$
$E_{th}$ → global p-value: $3.1 \times 10^{-3}$ → **2.7σ**

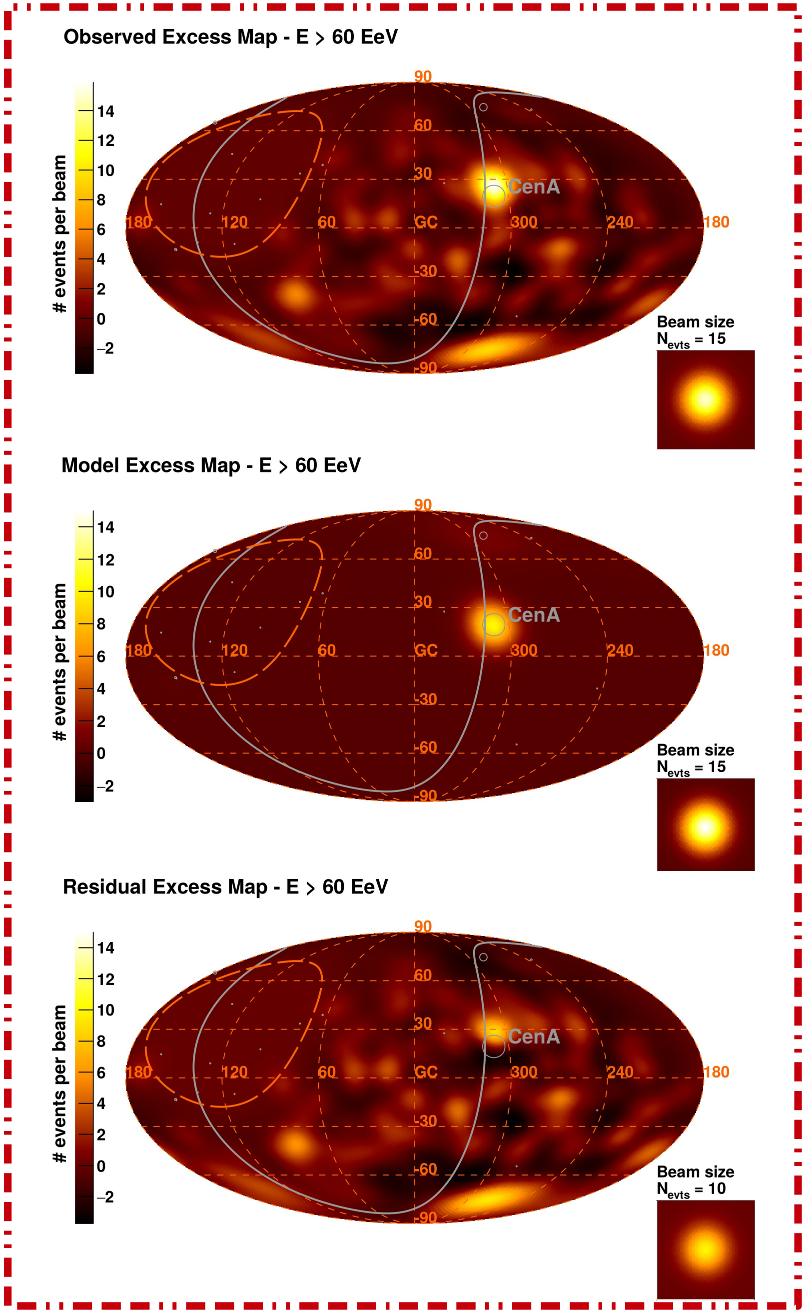


# Observations vs Expectations

Starburst galaxies




Active galaxies



# Alternative skies

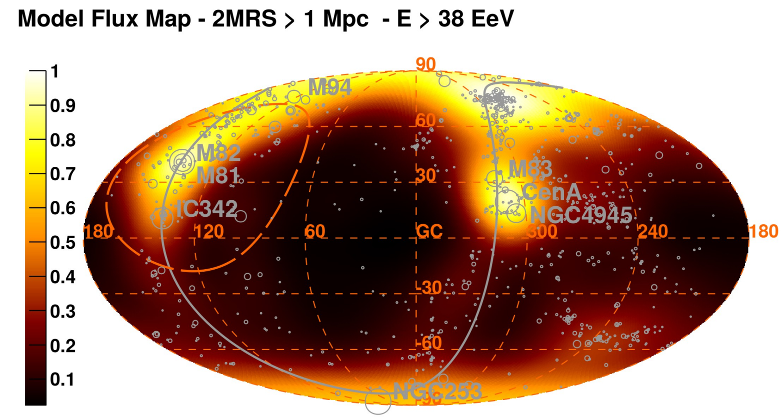
## 2MRS catalog

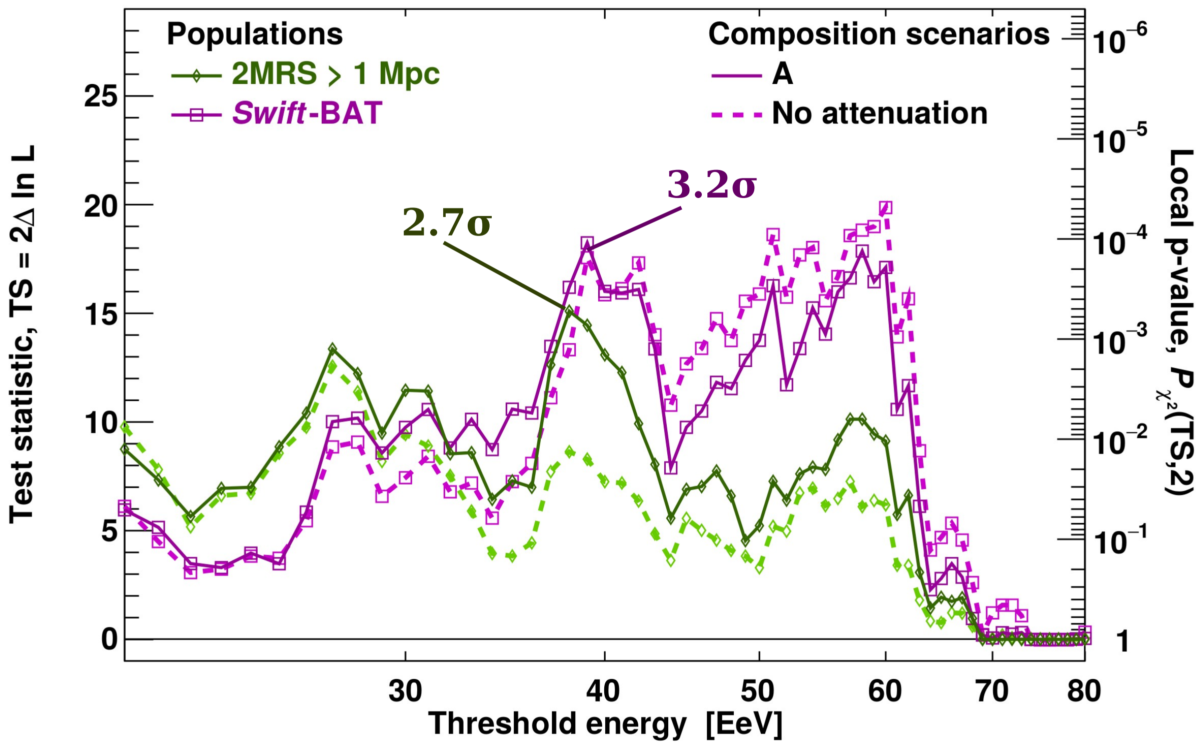
Infrared (K-band) flux corrected for Galactic extinction

> 1 Mpc (Local group excluded as in Erdogdu +06

Tracer of large-scale distribution of matter

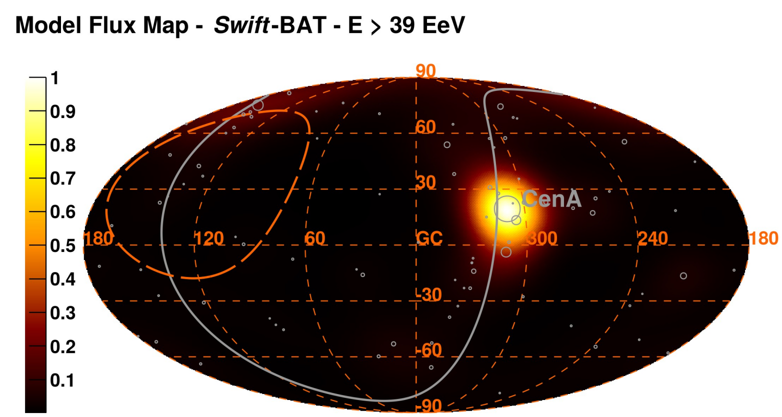
Bell, de Jong 2001



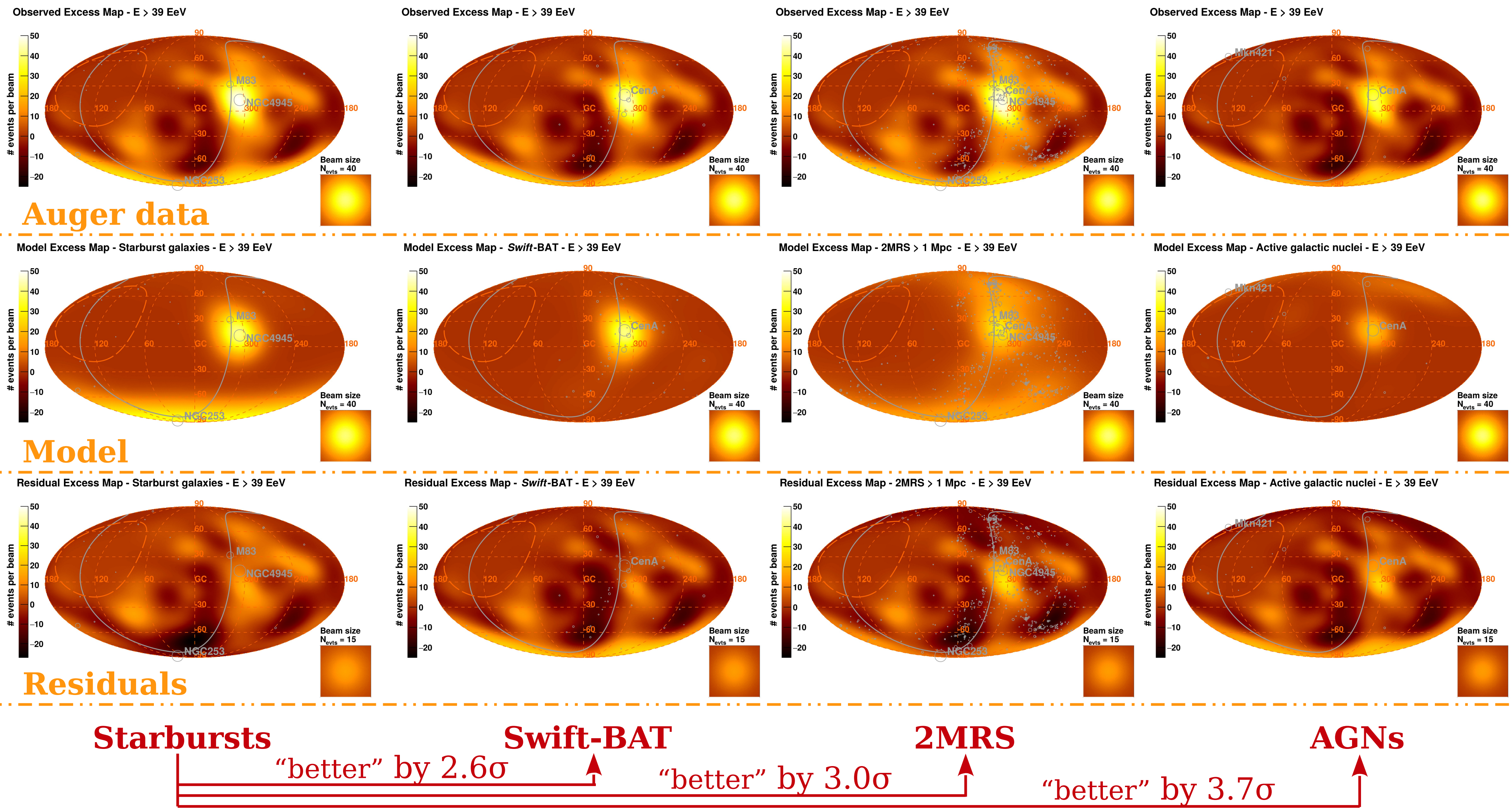




## *Swift*-BAT catalog

X-ray flux (14-195 keV): radio-loud & -quiet AGN, incl. starbursts (Sy)



# What is the best match for an UHECR > 39 EeV?




Likelihood ratio test: **ISO + α Starburst + β Other vs ISO + β Other**

**Starbursts: strongest anisotropy indication so far + preferred to other galaxies – but caution: magnetic fields!**

# Interpretation & Beyond

# Starburst galaxies - best-fit parameters

## Search radius

Simulations of 3 tested composition scenarios through the Galactic magnetic field of Jansson & Farrar 12

. 2 CNO-dominated scenarios → ~25°
. 1 p-dominated scenario → ~5°

→ **reconstructed parameters from sims bracket θ~13°**

**Composition > 40 EeV?**

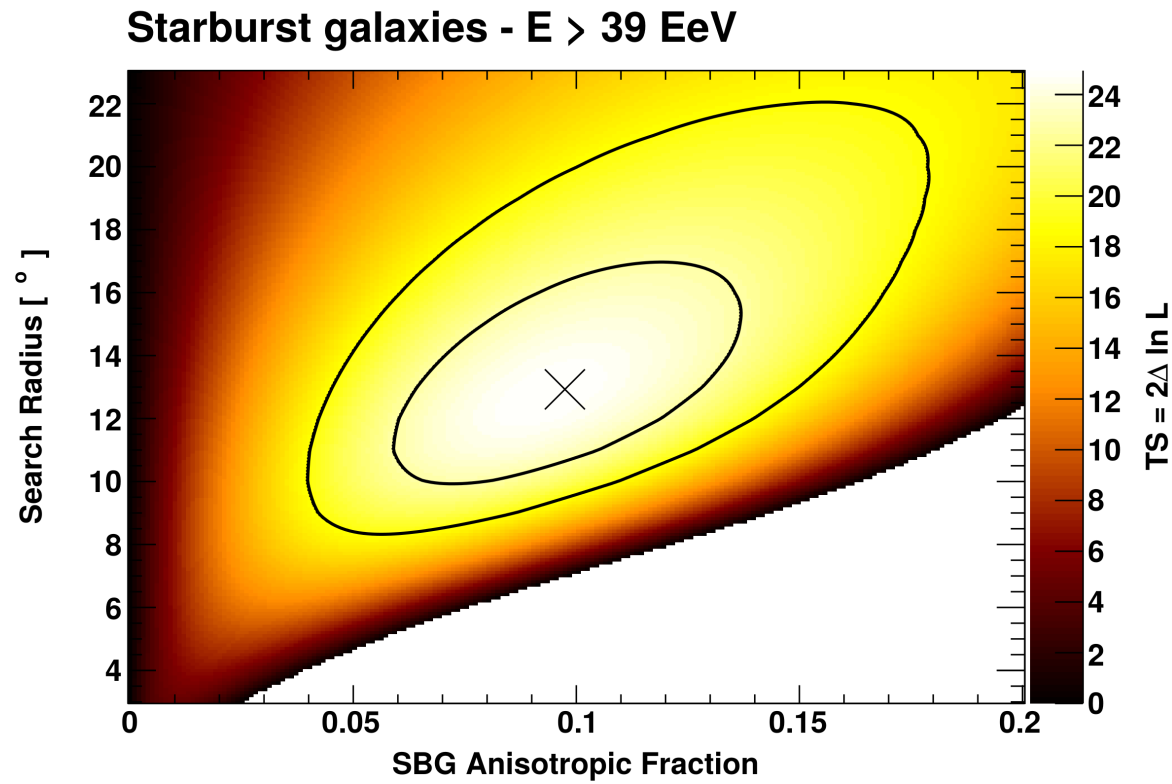
## Anisotropic fraction

10% of UHECR events correlating with position and flux of starbursts

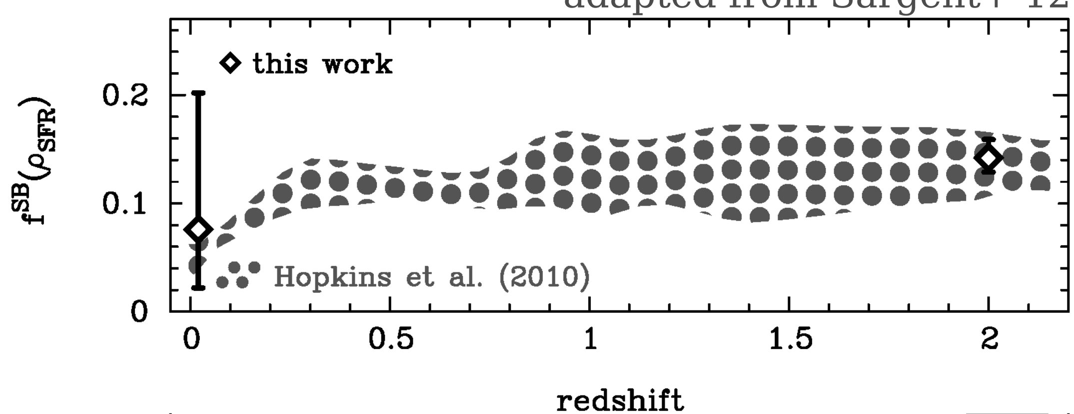
Other 90%? Heavier nuclei deflected further away? Unresolved sources?

Note: Starburst contribution to local starformation rate: 5-20% (Sargent+ 12)

→ Are starbursts the tip of the iceberg?




adapted from Sargent+ 12



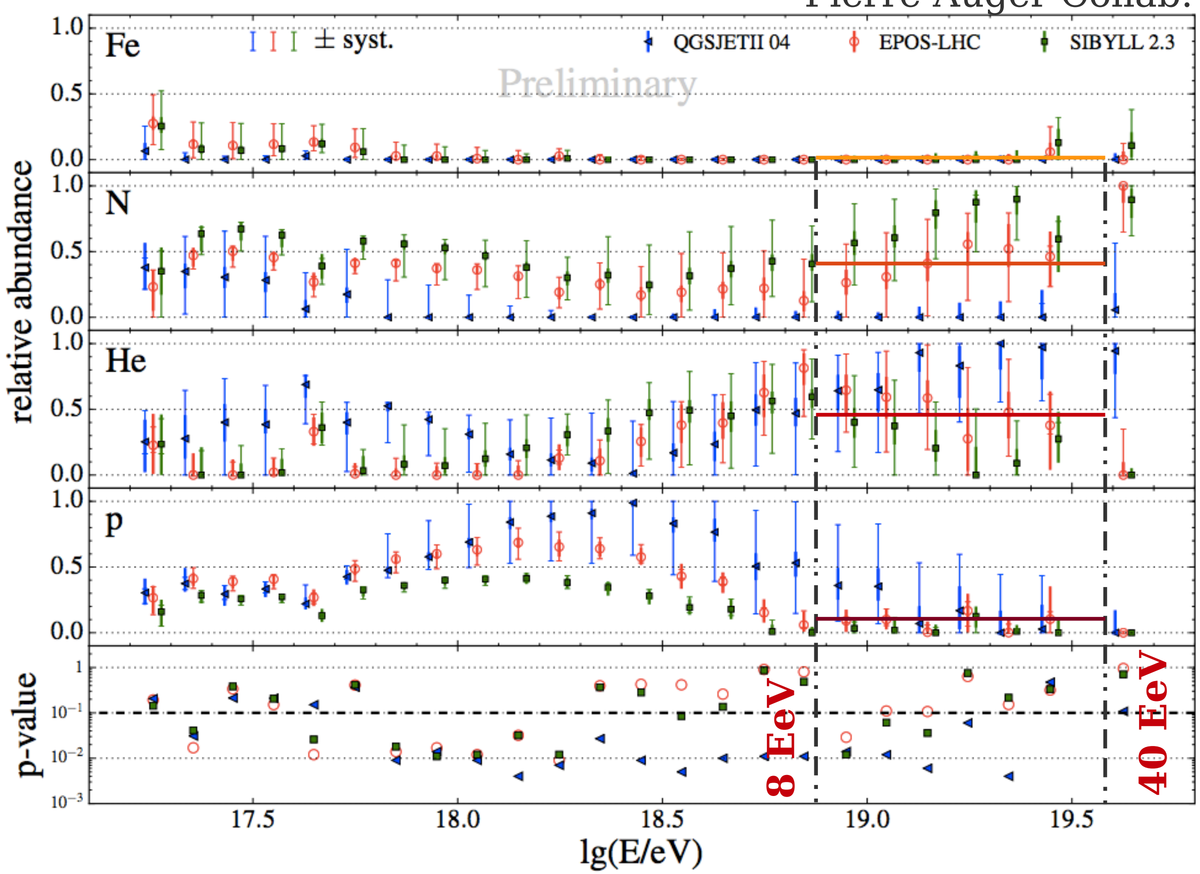
# Composition at the highest energies?

## Fluorescence data

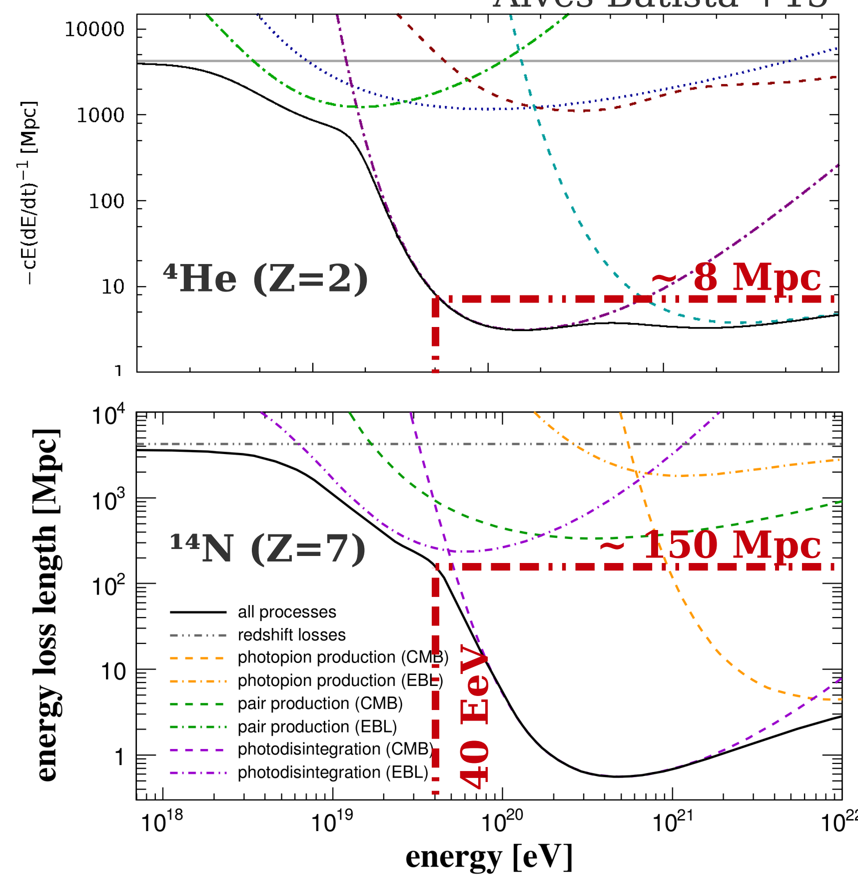
Point to few p and Fe > 8 EeV, with a possibly significant amount of He / N

*Note: systematics from interaction models rather large, run out of statistics > 40 EeV*

Pierre Auger Collab.




Alves Batista +15




## A possible signature of very nearby sources

$^4$He doesn't travel far ↔ NGC 4945, M 83, NGC 253, M82 located 3-4 Mpc away!

# Auger upgrade

## Highest energies: components

. 3.8 m² scintillators on each water-cherenkov tank
. upgraded electronics + extra PMT (dynamic range)

→ improved characterization of electromagnetic & muonic components of the shower

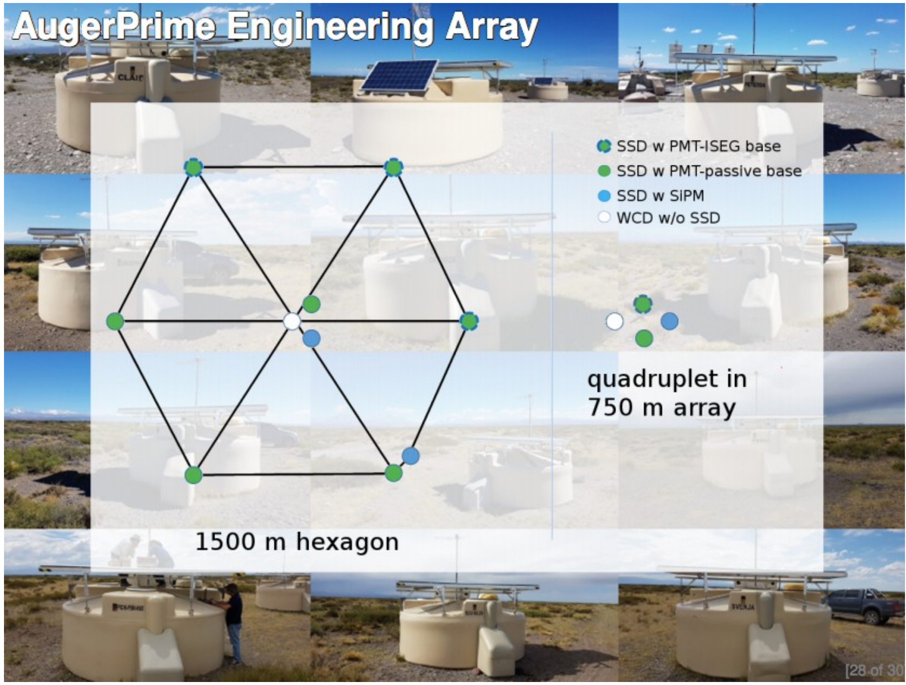
→ $N_\mu(E)$ correlated to $X_{max}(E)$ → **better compo.**

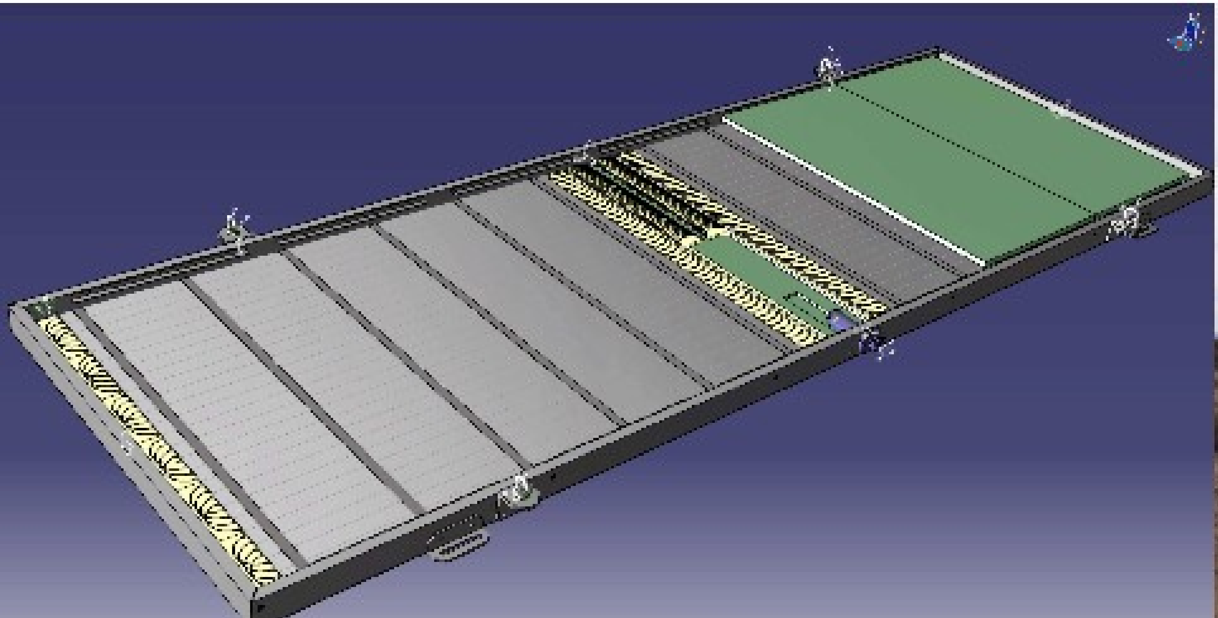
e.g. Parra +16

## Lower energies: components

. Burried muon counters in infill array (AMIGA)

. Increased fluorescence uptime



# Complimentary approach: full sky coverage

## Telescope Array hotspot

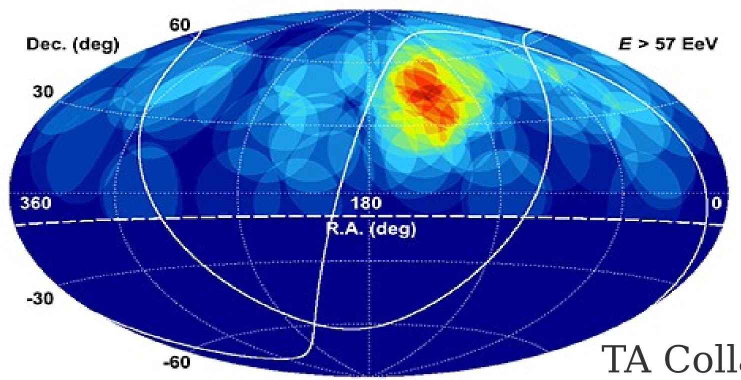
. Array of 700 km² in Utah (ongoing upgrade x 4) → Northern hemisphere

. Excess of 15 evts (3.4σ) for $E_{TA}$ > 57 EeV in a 20° region at Dec ~ 45° **± ??**

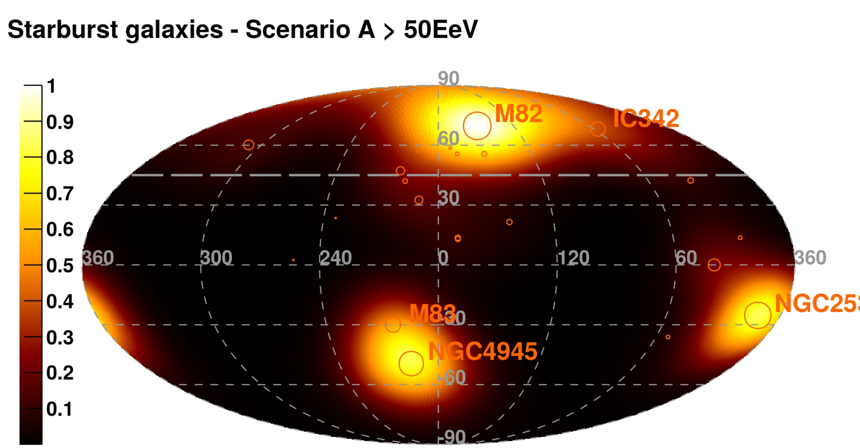
## Combining Auger and TA data?

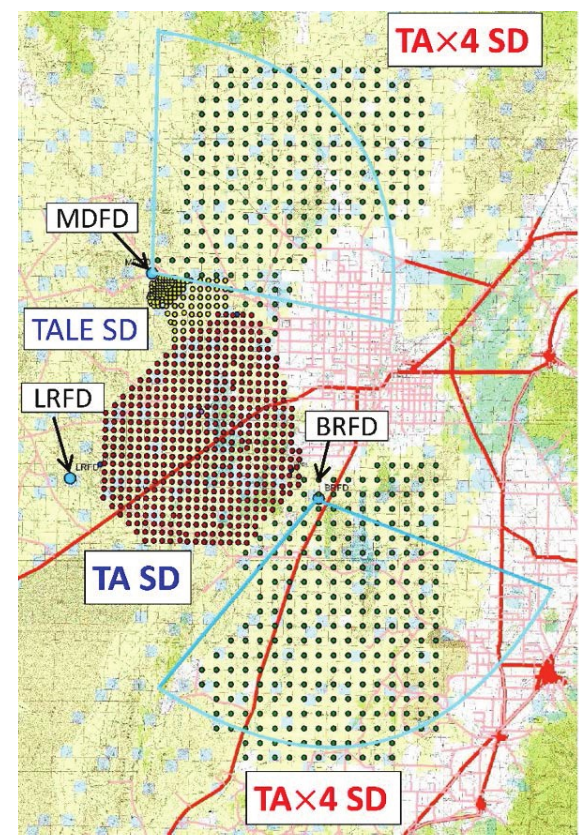
. Match of the TA hotspot with M82 excess? Combination accounting for ≠ E-scale?

first efforts >10EeV: Di Matteo +17 (UHECR16)




TA Collab. 14



# Conclusion

# Back to >75yrs old mission:

**Who Is Shooting Superfast Particles at the Earth?**

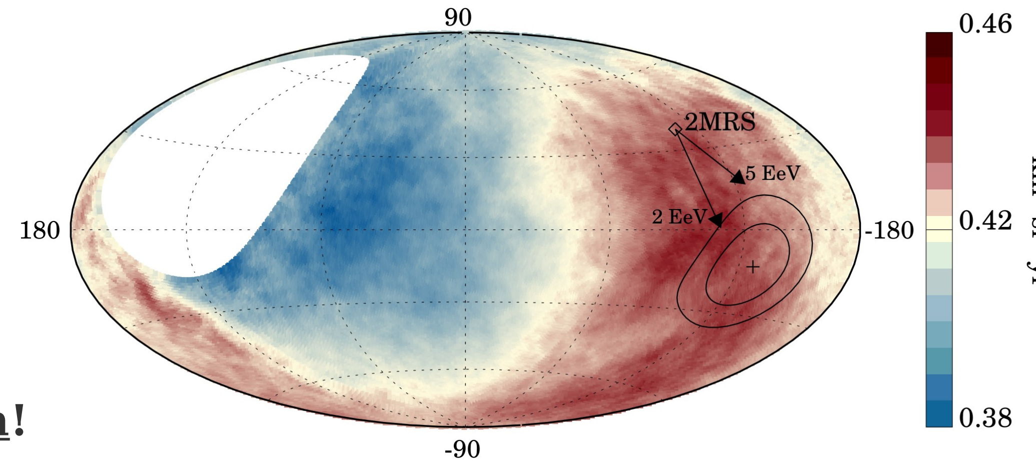
## First harmonic study > 8 EeV

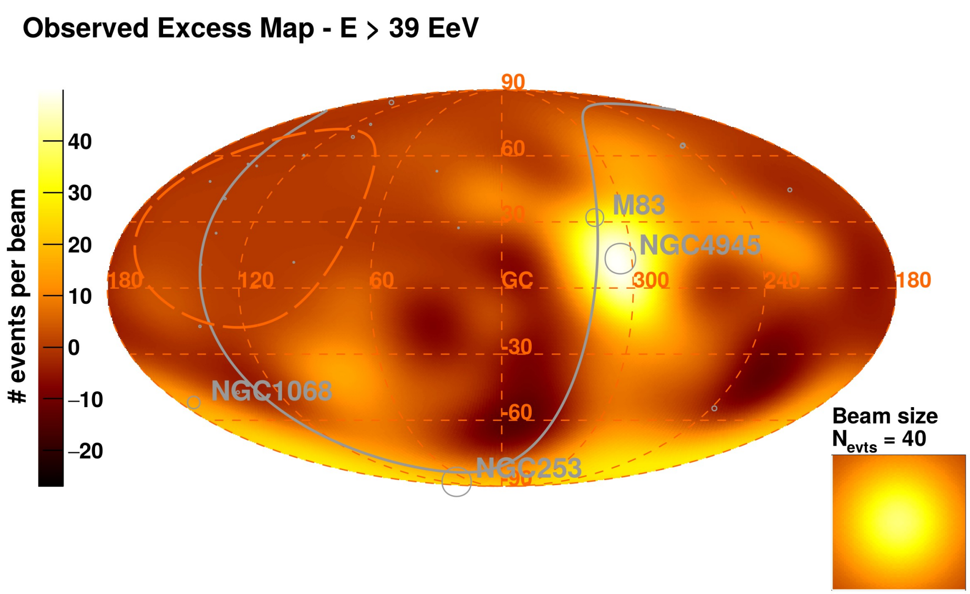
. Collection of > 30,000 events
→ **5.4σ anisotropy**

## 1st order spherical expansion

. 6.5% dipole compatible with galaxy distrib.

→ **1st obs. evidence of extragalactic origin!**




## Max-likelihood analysis > 40 EeV

. Collection of ~900 events
→ **4.0σ starburst-based anisotropy**

## We still don't know the sources!

. Starbursts only preferred to other galaxies by ~3σ

. **More to come**: models (magnetic fields) current data (Auger+TA), upgrades!

# Back to >75yrs old mission

Nous savons certainement beaucoup plus de choses sur le rayonnement cosmique qu'à l'époque où nous nous étions placés pour faire le premier tour d'horizon. Mais ces connaissances sont encore bien insuffisantes pour offrir au sujet de l'origine de ce rayonnement autre chose que des indications ~~négatives~~. Ne nous en plaignons pas ; si l'on savait tout, il n'y aurait plus autant de plaisir à s'occuper d'une science qui serait devenue alors comparable à une langue morte. Nous devons nous estimer heureux d'avoir toujours devant nous de nouveaux problèmes dont l'aspect original est un des principaux stimulants de la recherche.

Appliquons joyeusement à leur solution toute la puissance de notre logique et de notre imagination : la science ne sera pas ingrate. La réalité, que nous découvrons en écartant pli par pli le voile d'Isis, se montrera toujours supérieure en beautés imprévues aux systèmes échafaudés par l'esprit humain lorsqu'il est abandonné à ses seules ressources.