The UHECR science after >15 years of operation of the Pierre Auger Observatory

O. Deligny (CNRS/IN2P3 - IJCLab Orsay)

i) The Pierre Auger Observatory

ii) Searching for sources in arrival directions

iii) Energy spectrum and mass composition: probing source properties

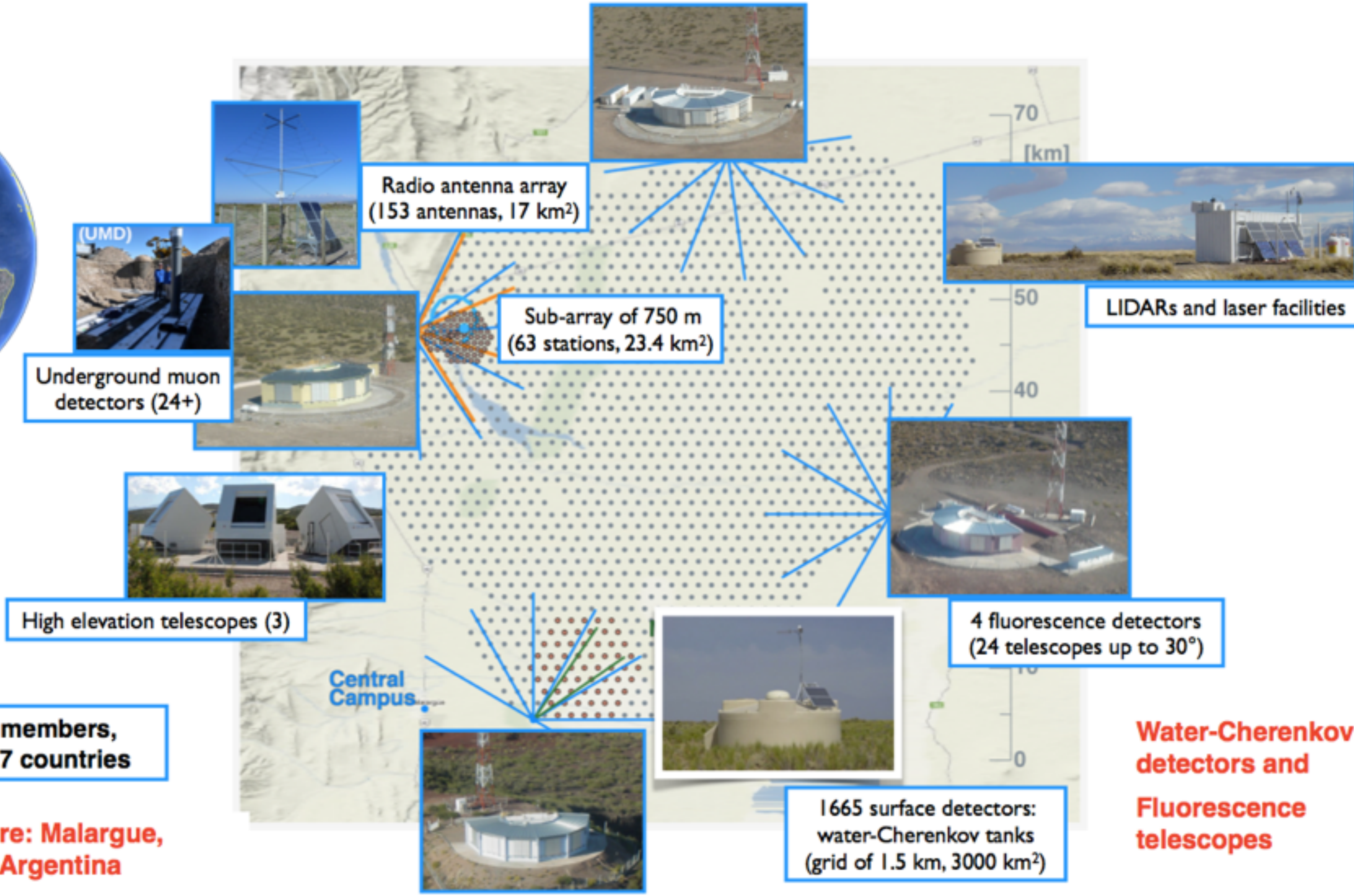
iv) Puzzles in extensive air showers

v) Photons, neutrinos, (super-heavy) dark matter

CRIS 2022
12th Cosmic Ray International Seminar
Naples, Italy, September 12 -16, 2022

i) The Pierre Auger Observatory

The Pierre Auger Cosmic Ray Observatory



More than 400 members,
98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

Water-Cherenkov detectors and

Fluorescence telescopes

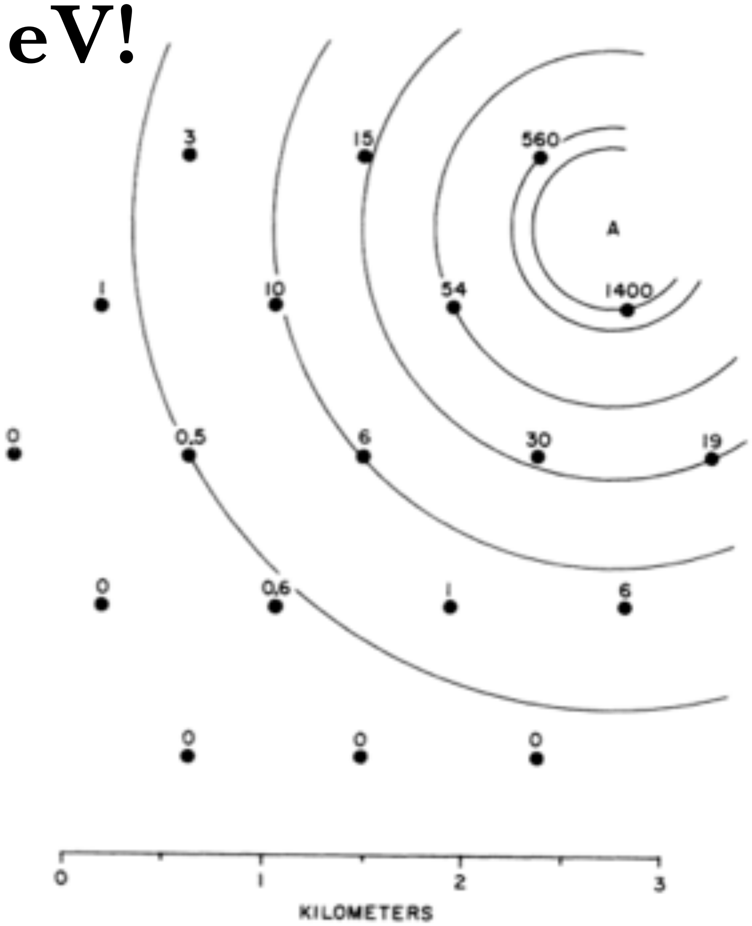
[NIM 798:172–213, 2015]

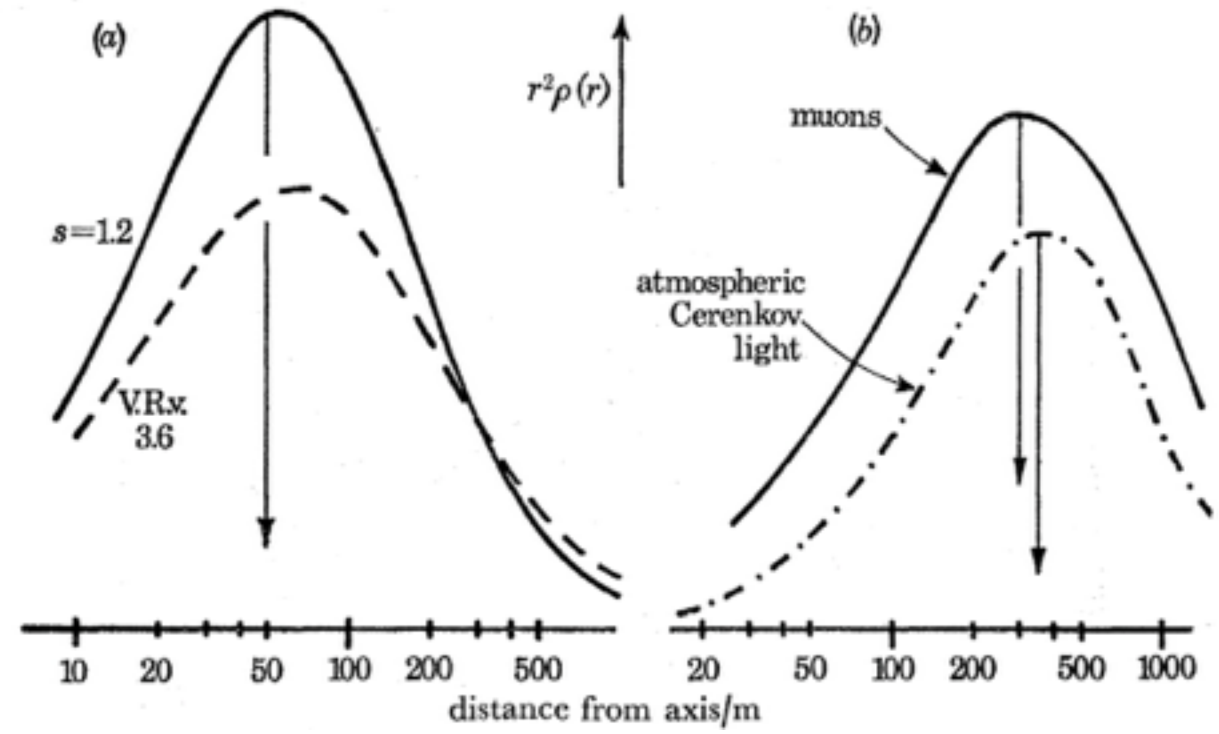
SD: Track-length integral from lateral sampling?

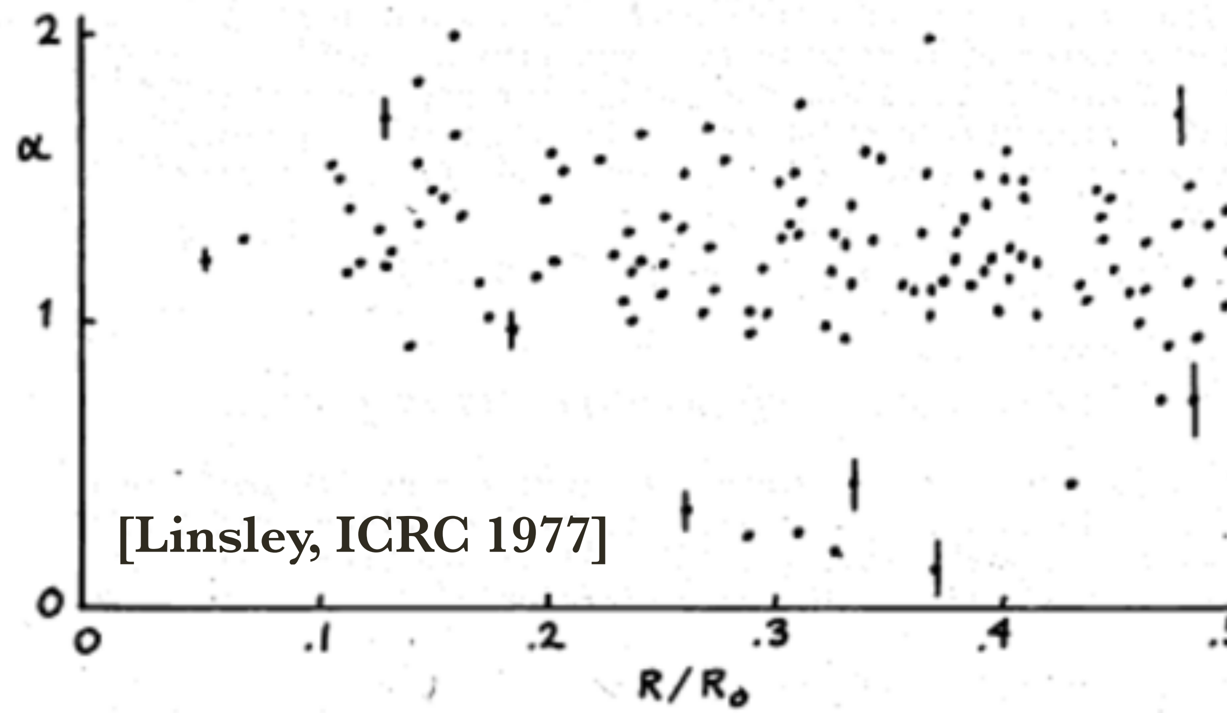
Issue: spacing of detectors > Molière radius

[Linsley, PRL 10:146–148]

~10^{20} eV!



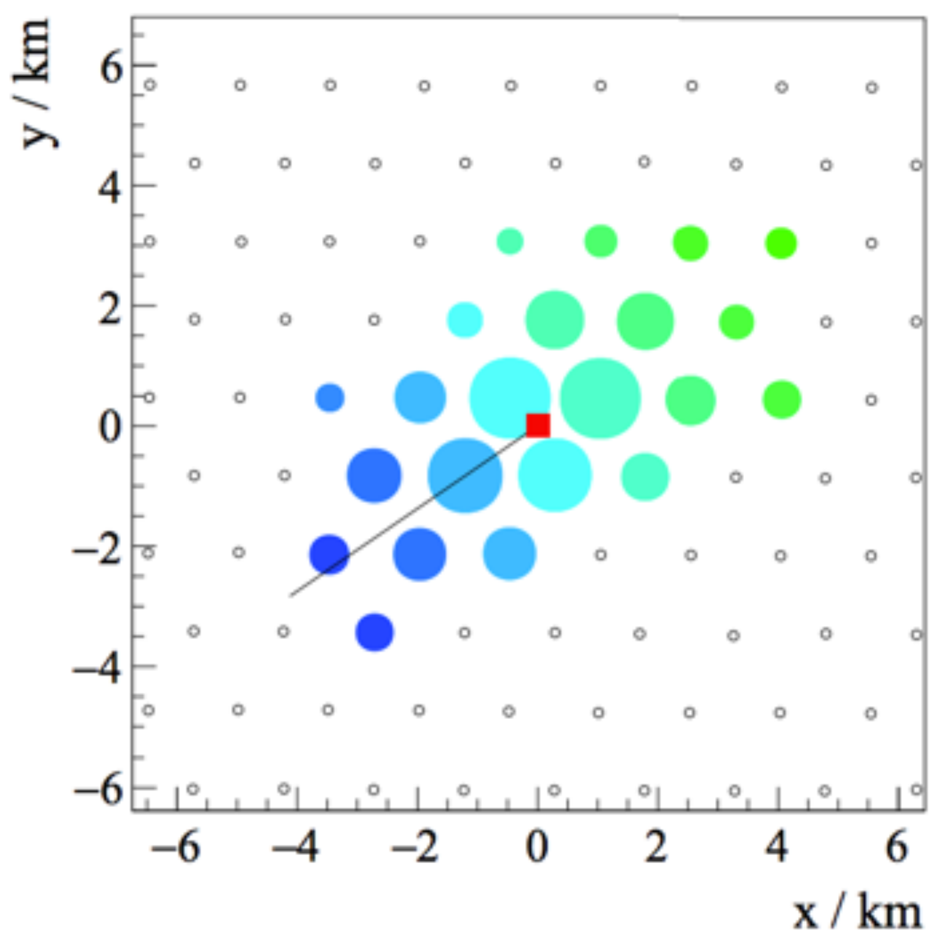


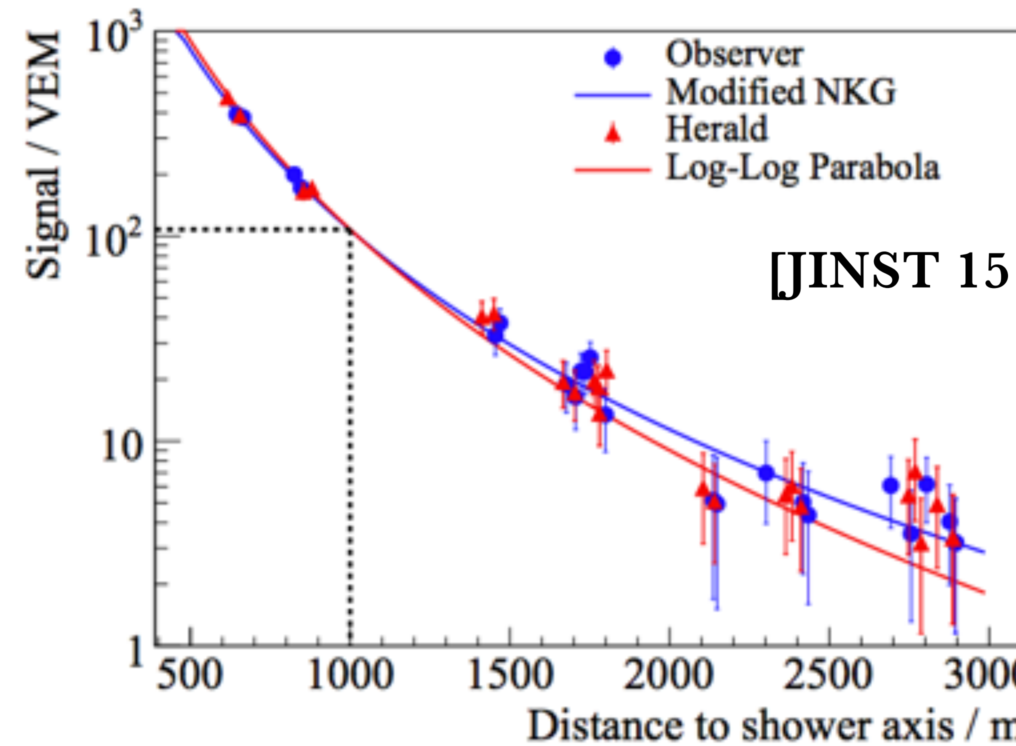


[Linsley, ICRC 1977]

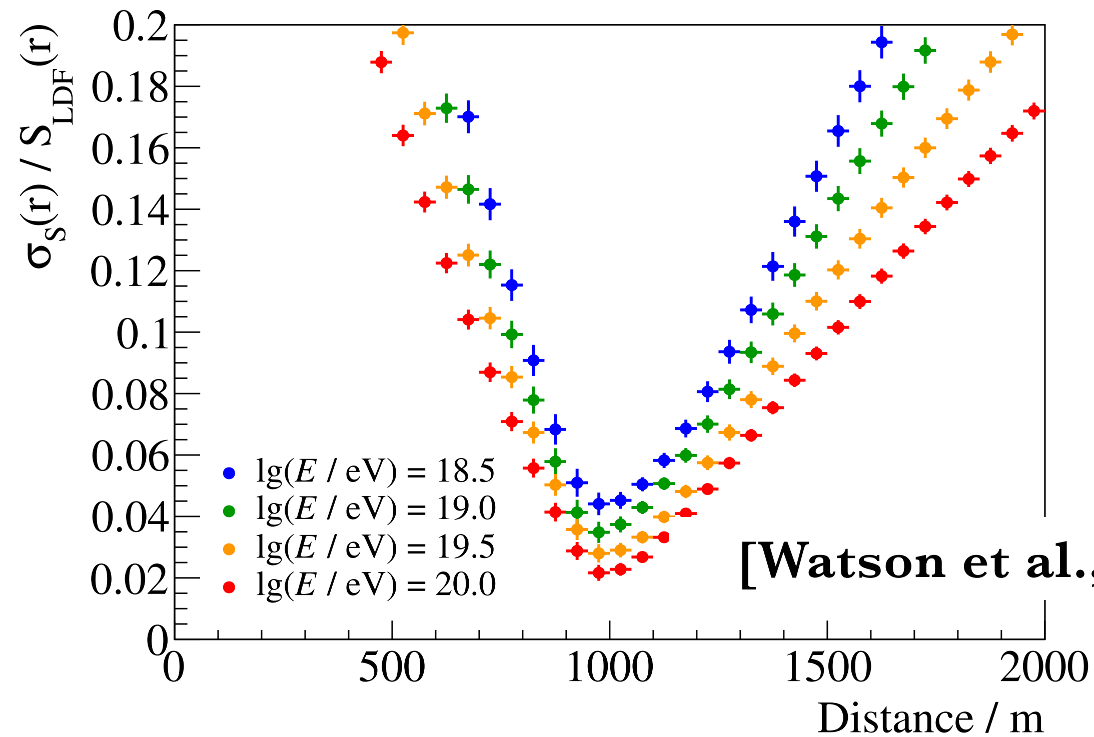
Track-length integral → Air-shower size

$S(r_{\rm opt})$ as shower-size estimate **[Hillas, Acta Phys. Acad. Sci. Hung., 29, Suppl. 3, page 355]**



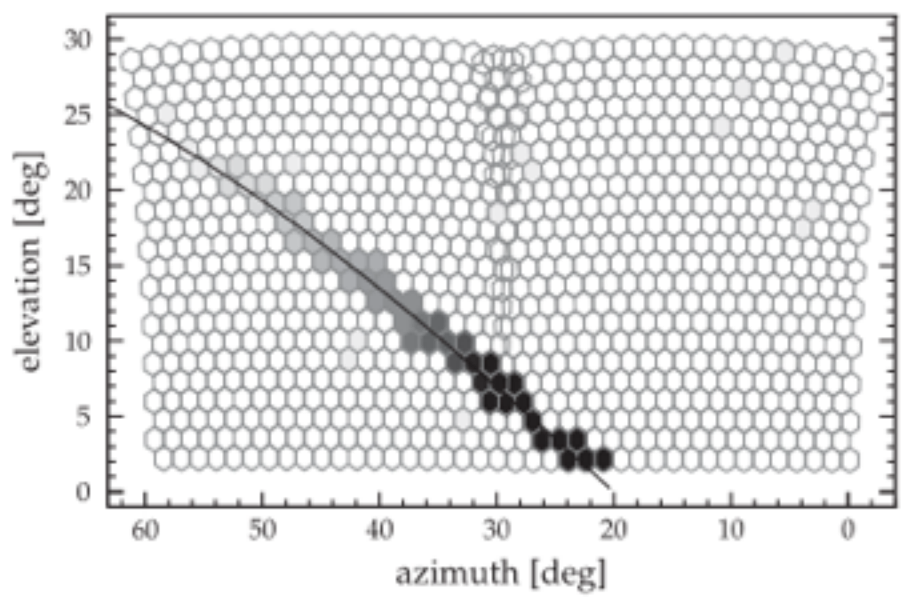


[JINST 15 (2020) P10021]

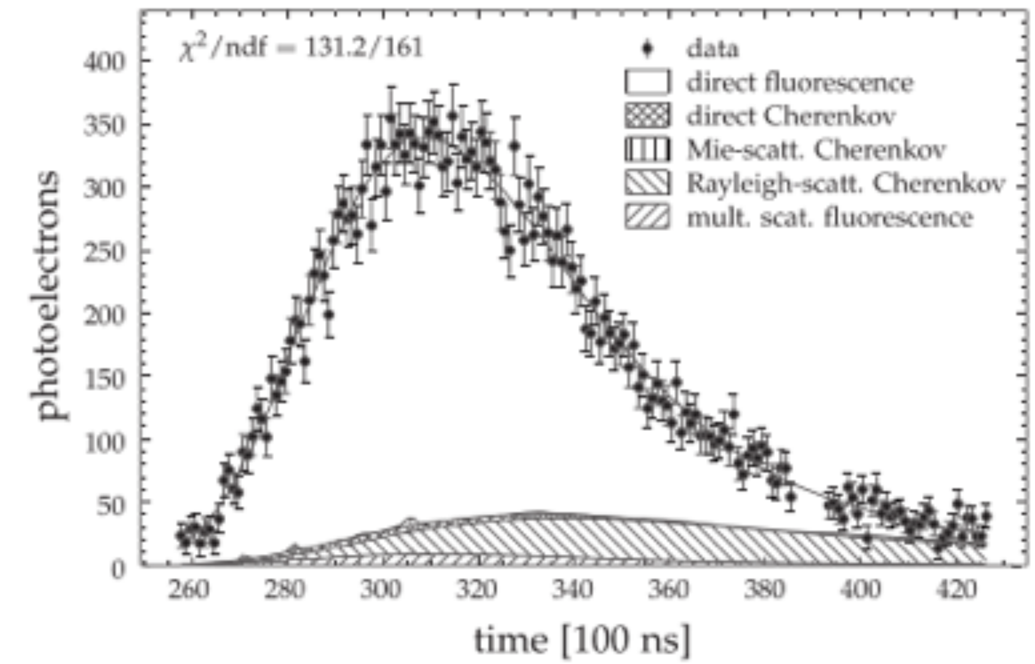


[Watson et al., ECRS 2022]

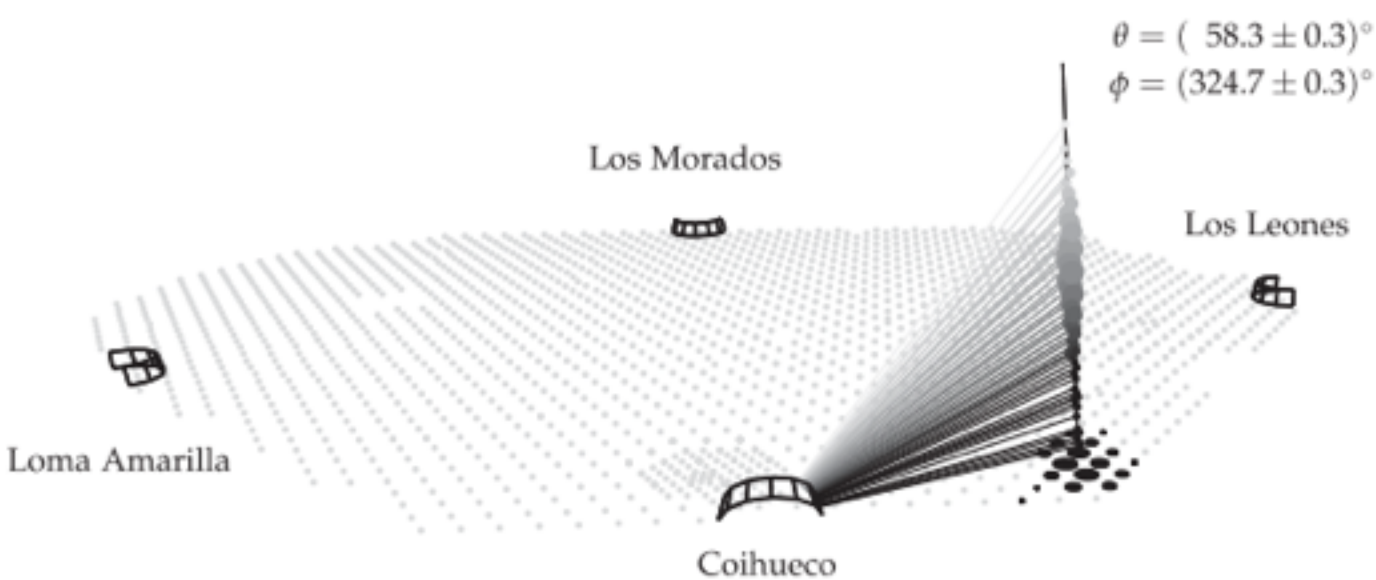
Longitudinal profile reconstruction



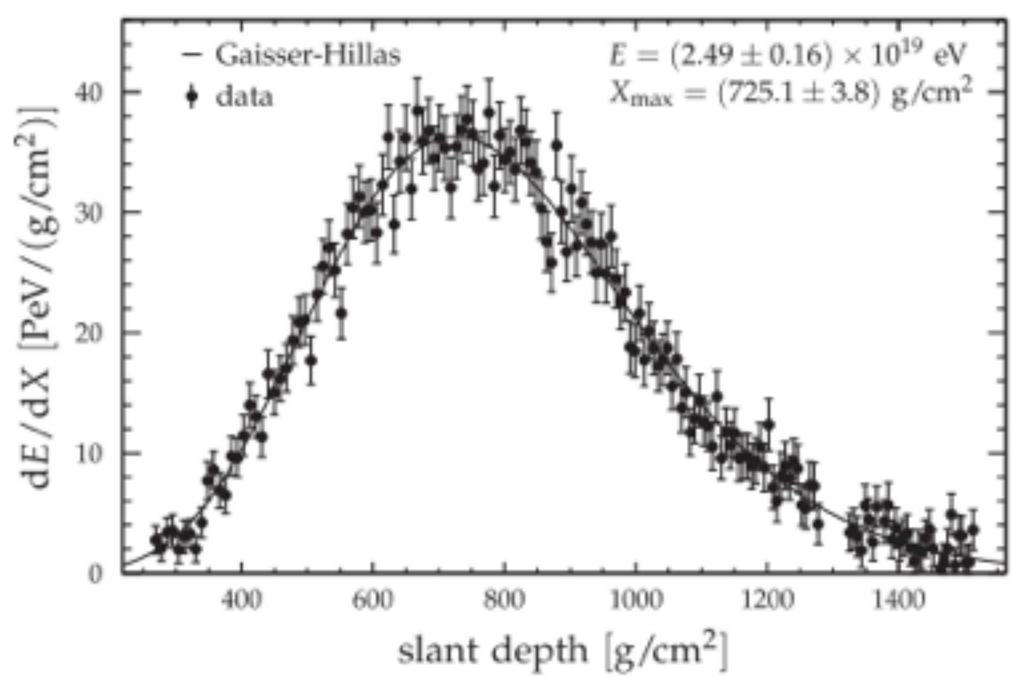
(a) Camera view. The timing of the pixel pulses is denoted by shades of gray (early = light, late = dark). The line shows the shower detector plane.



(c) Detected photoelectrons (dots) and the fitted contributions from components of the shower light (open and hatched areas).



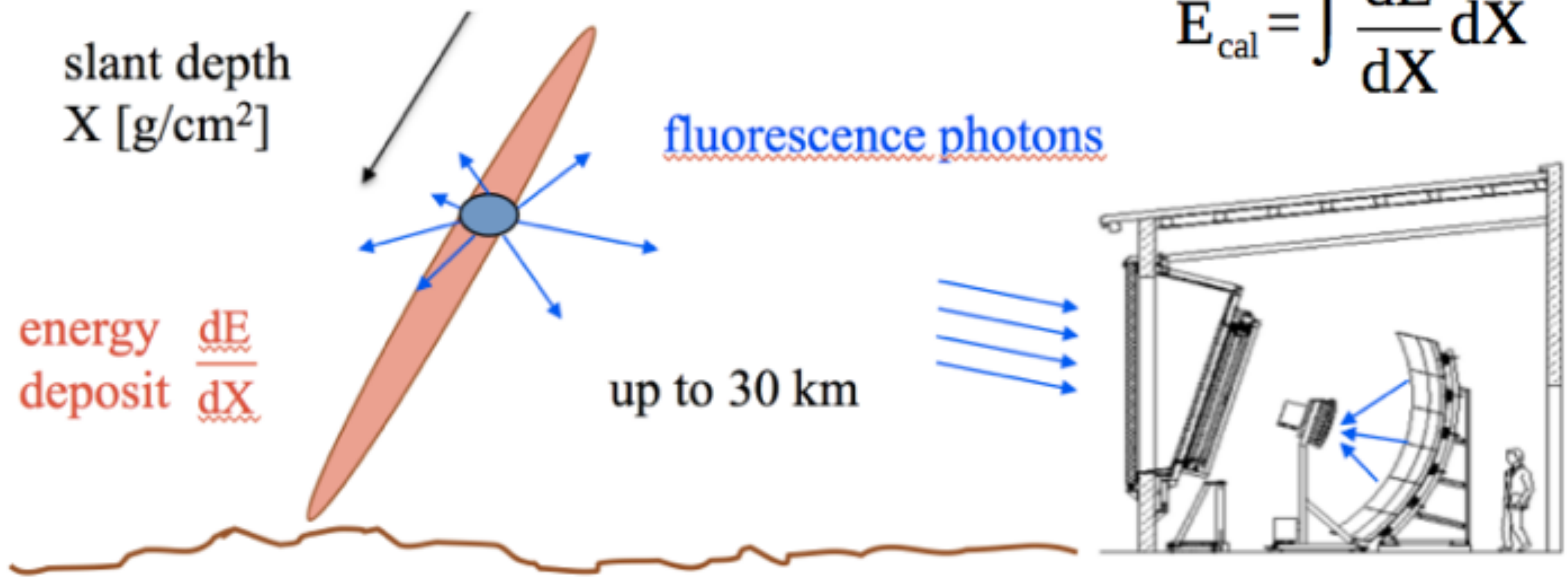
(b) Event geometry. Pixel viewing angles are shown as shaded lines and the shower light and surface detector signals are illustrated by markers of different size in logarithmic scale.

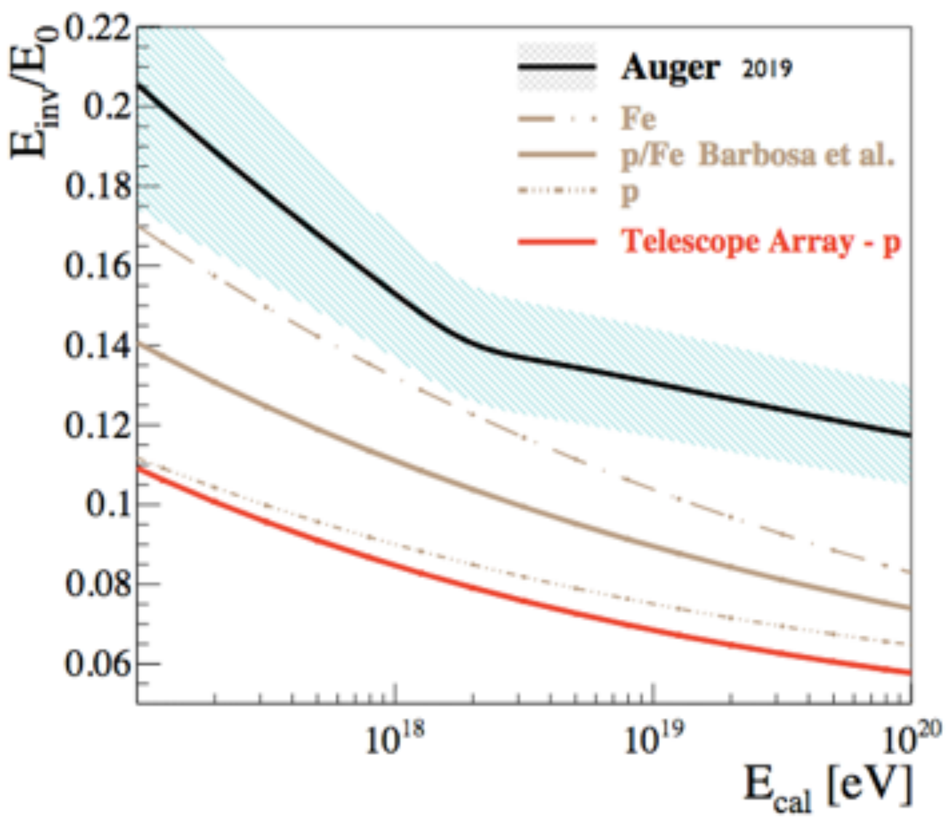


(d) Longitudinal profile (dots) and Gaisser-Hillas function (line).

Energy scale

$$E_{cal} = \int \frac{dE}{dX} dX$$





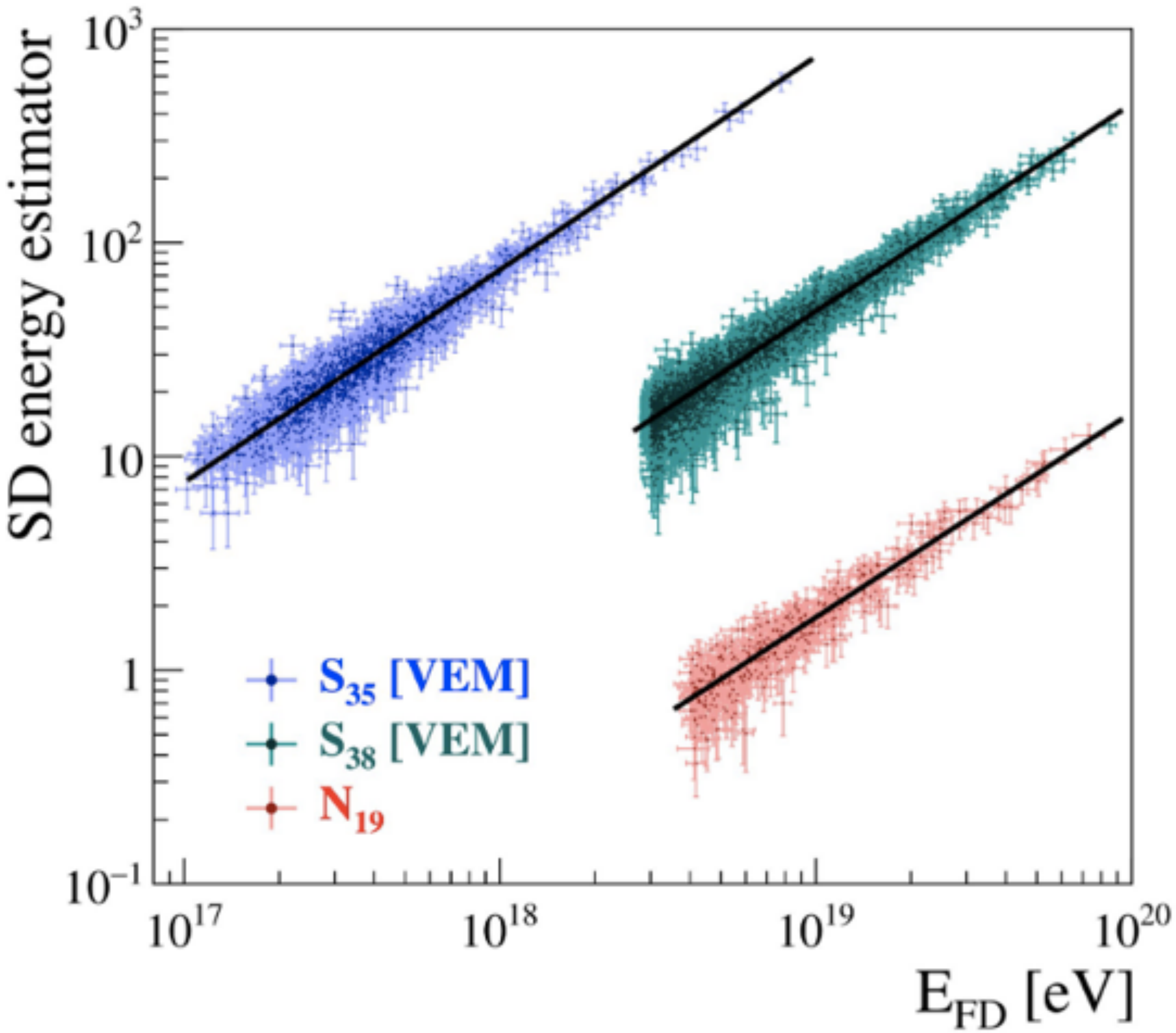
[PRD 100 (2019) 082003]

Systematic uncertainty in the energy scale	
Fluorescence yield	3.6%
Atmosphere	3.4% – 6.2%
FD calibration	9.9%
FD profile recon.	6.5% – 5.6%
Invisible energy	3% – 1.5%
Stability of energy scale	5%
TOTAL	14%

From 3×10^{18} eV to highest energies
- similar at lower energies

[Dawson, ICRC2019]

Propagation of FD energy scale



SD data are calibrated to FD energies
- common energy scale

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

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

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

Power-law *extrapolation*: no break in ER required

ii) **Searching for sources in arrival directions**

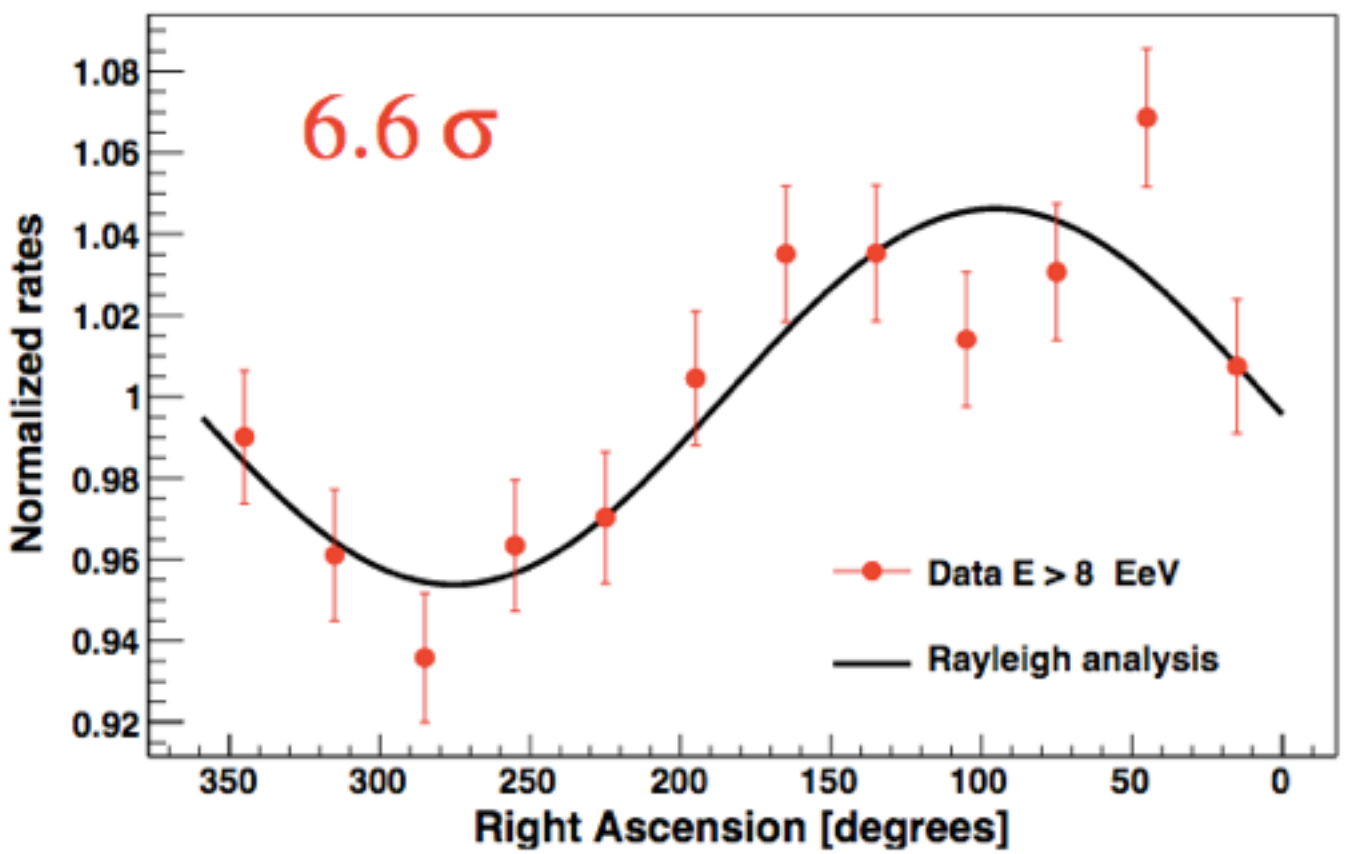
➡ Aiming to capture in the UHECR arrival directions a pattern suggestive in an evident way of a class of astrophysical objects.

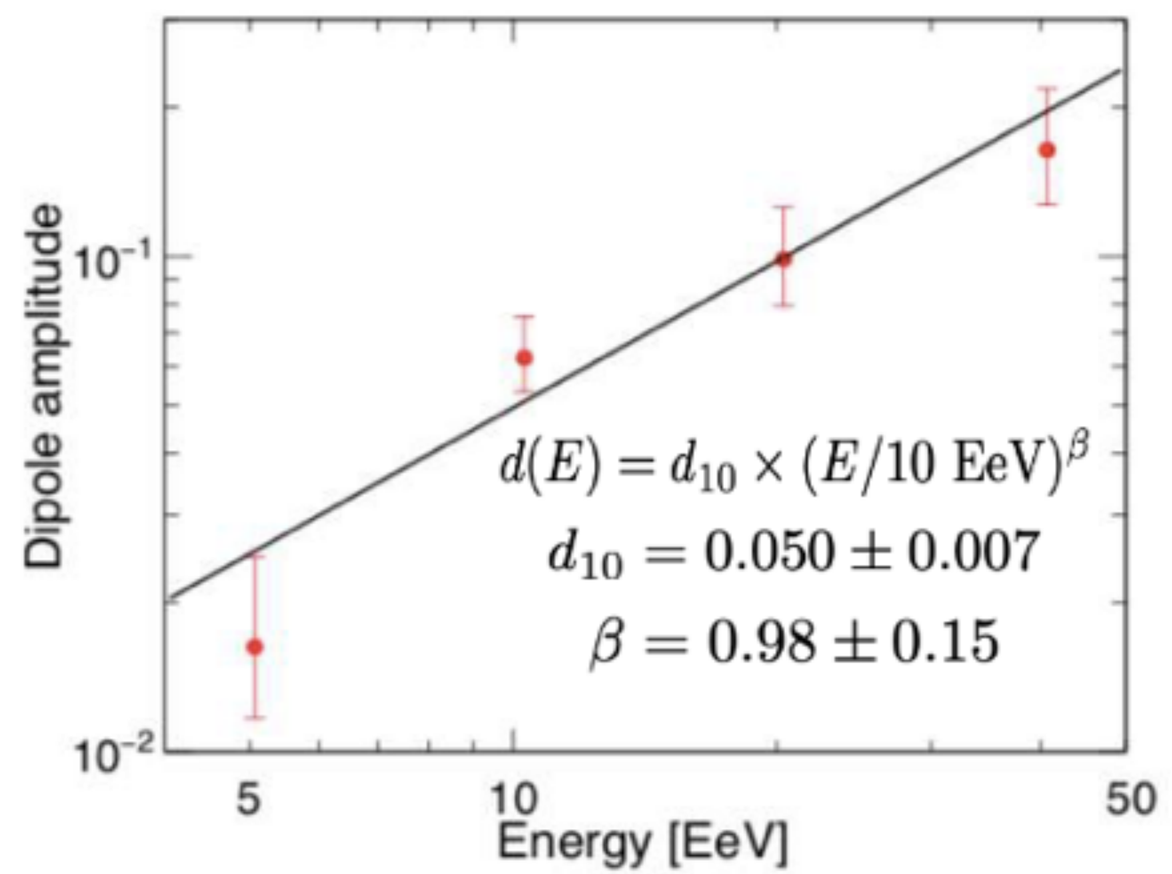
First harmonic in RA

- Control of the event rate/directional exposure in right ascension

➡ Fourier expansion of the directional intensity

[Science 57 (2017) 1266, ApJ 868 (2018) 1]





Extragalactic origin

Laniakea: Norma (attractor) + Pavo-Indus + Virgo supercluster (Virgo cluster + Local sheet)

Local sheet : 10-15 Mpc diameter, 0.5 Mpc height, with a void region ~70 Mpc North in supergalactic coordinates

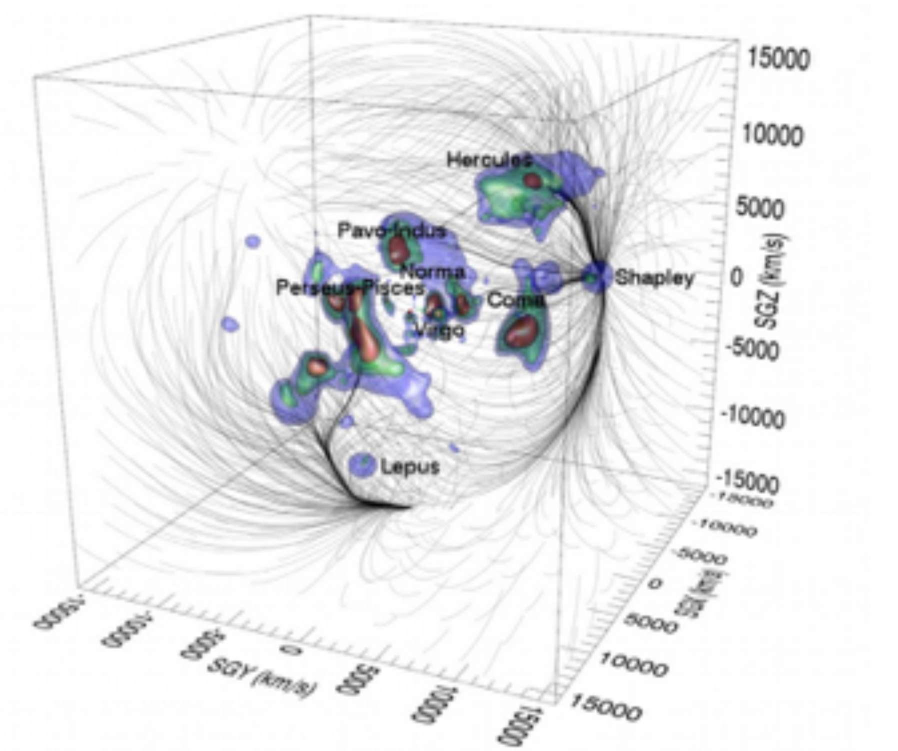
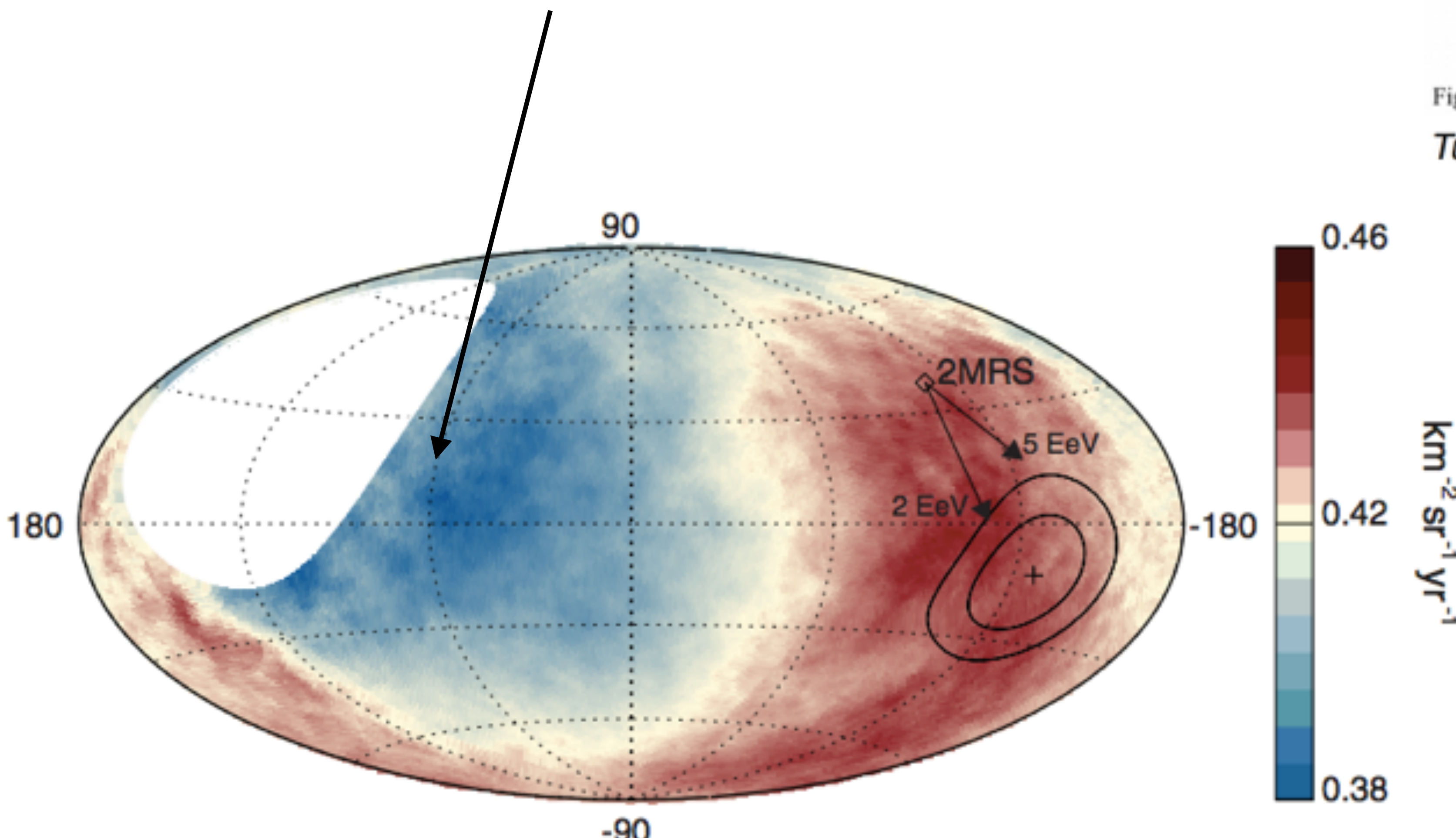


Fig. ED 1. — Structure within a cube extending 16,000 km s^{-1} (~200 Mpc)

Tully, Courtois, Hoffman, Pomarède, Nature 2014

Direction of the local void



[Science 57 (2017) 1266]

Accounting GMF deflections

[Jansson and Farrar ApJ 757 (2012) 14]

Z ~ 1.7 – 5 at 10 EeV ⟶ E/Z ~ 2 – 5 EeV

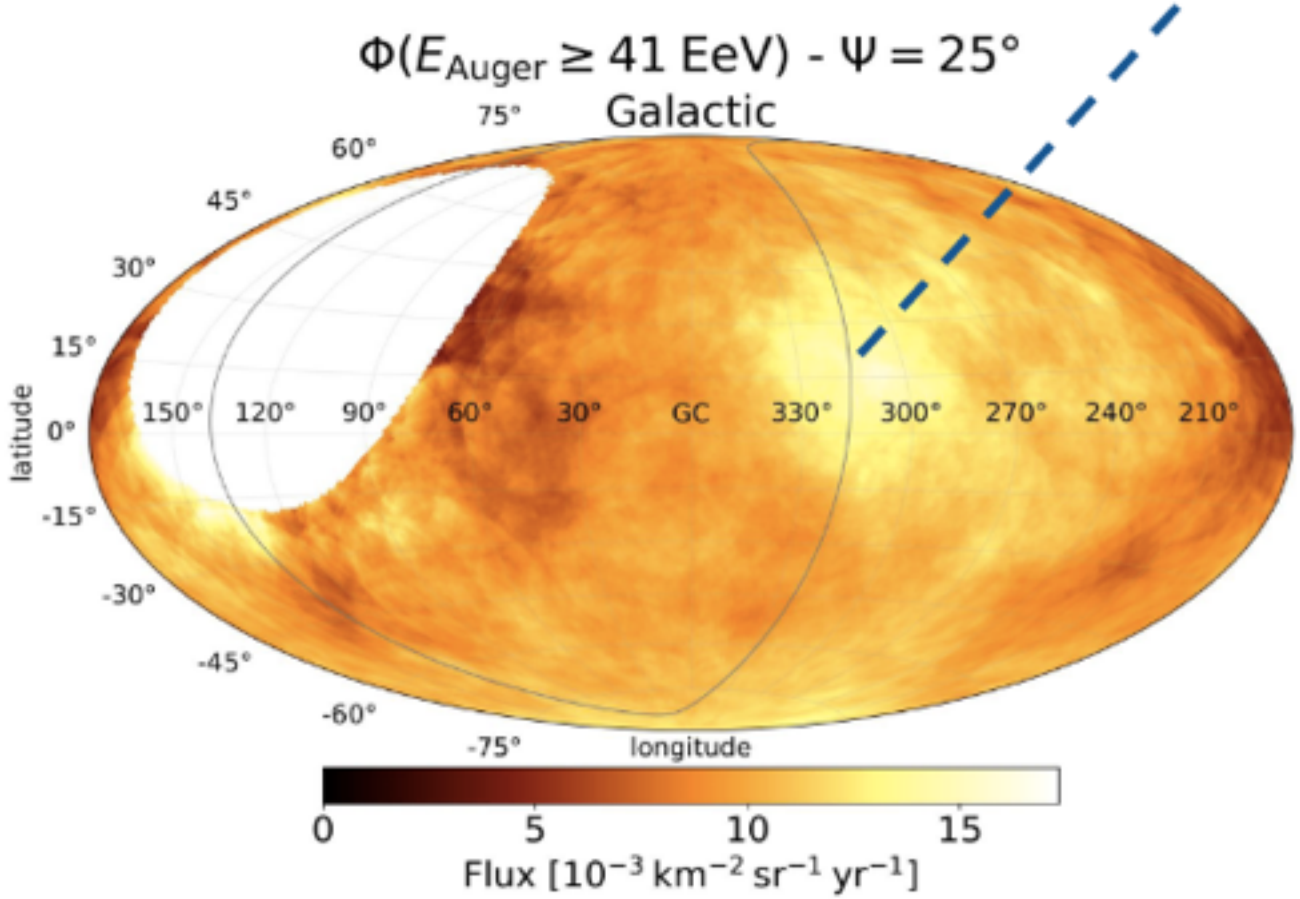
[Auger Coll. PRD 90 (2014) 122006]

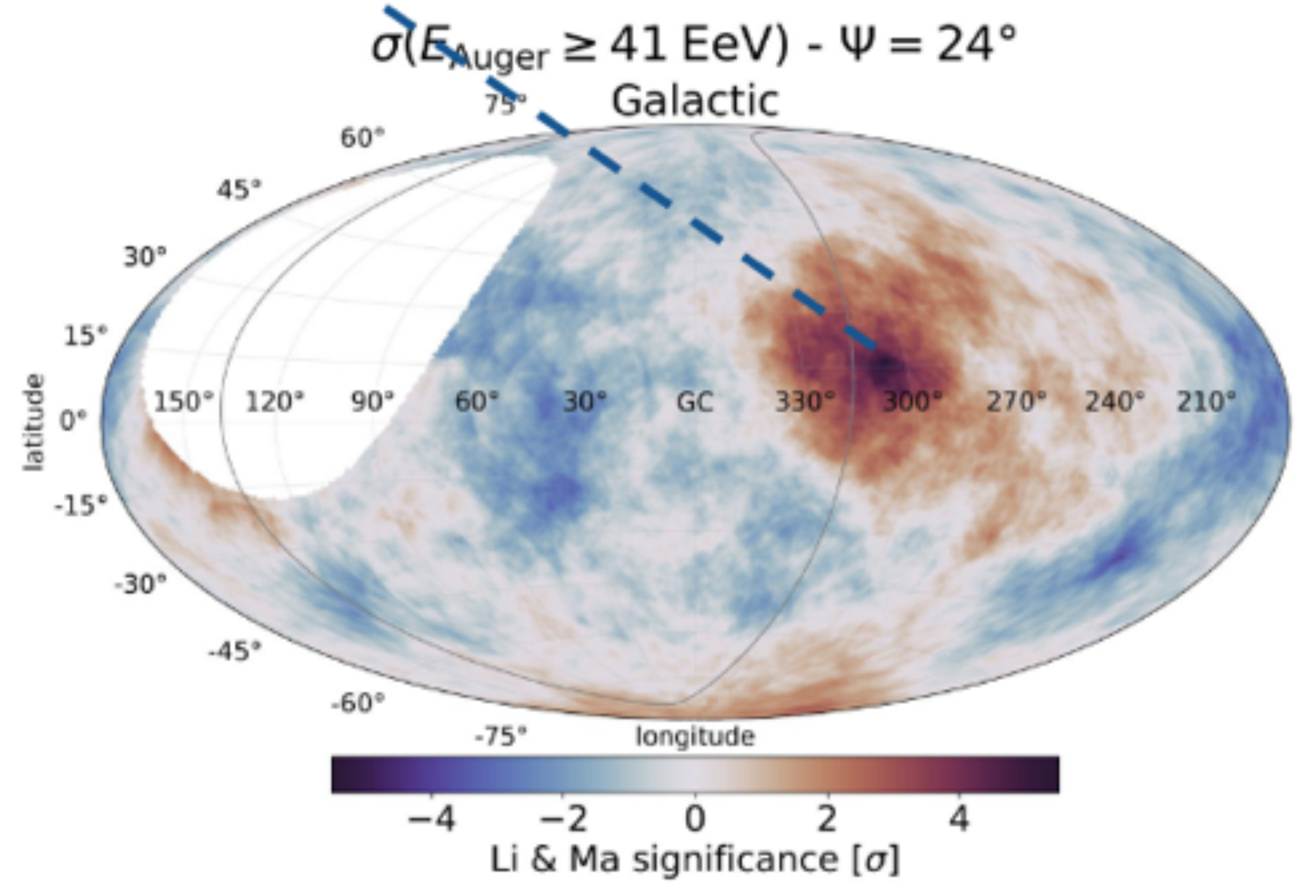
Blind searches for over-densities

Parameter space is scanned in

- Direction (R.A., Dec)
- Threshold energy Eth = {32, 80} EeV
- Top-Hat angular scale Ψ

Largest significance post-trial **2.2σ**
found at (RA, dec)=(196.3°, -46.6°) or (l, b)=(305.4°, 16.2°)
Nobs = 156 vs Nexp=98 at Eth 41 EeV and Ψ=24°





[ApJ 935 (2022)170]

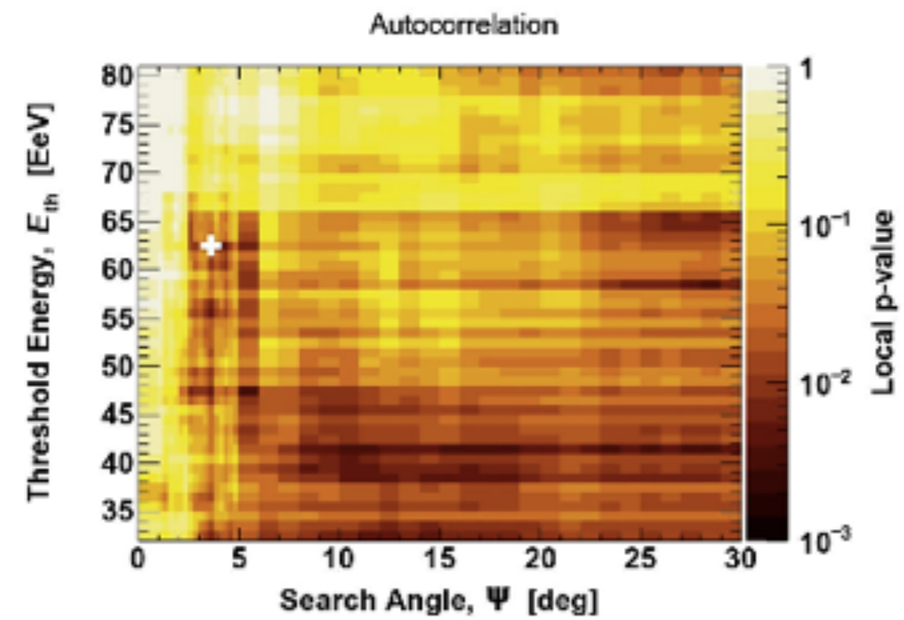
Autocorrelation and correlation with structures

Structures

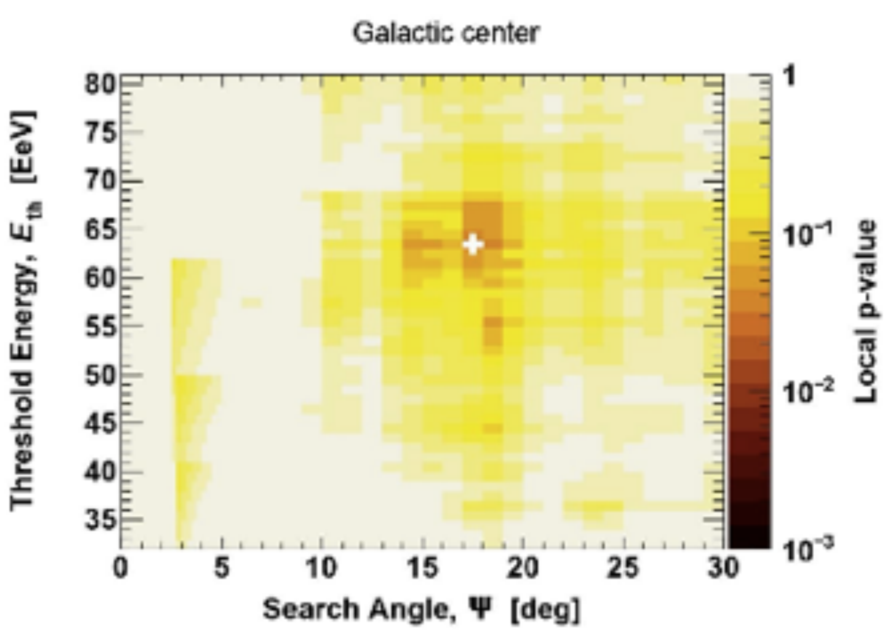
Events in proximity of local astrophysical structures
Scan in threshold energy, angle Ψ

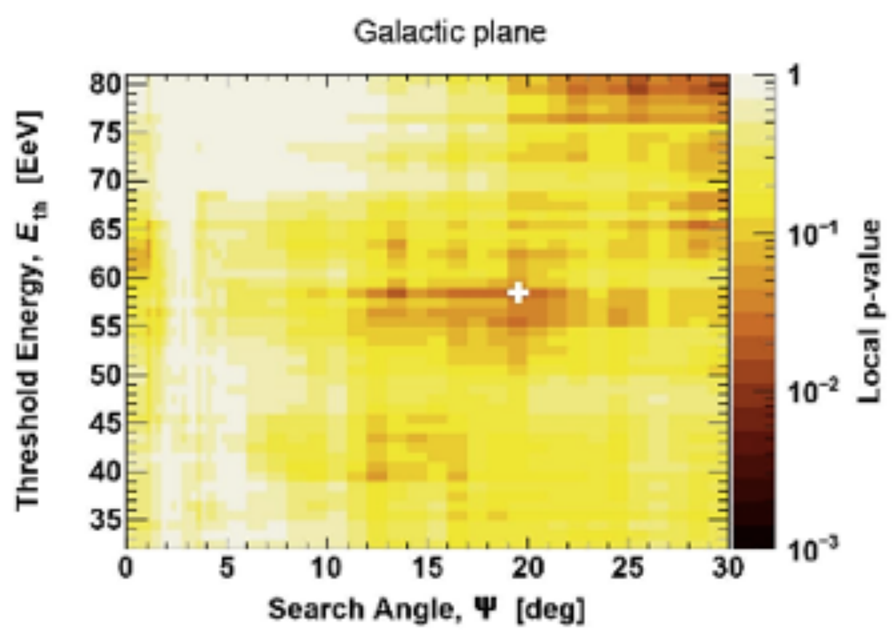
Autocorrelation

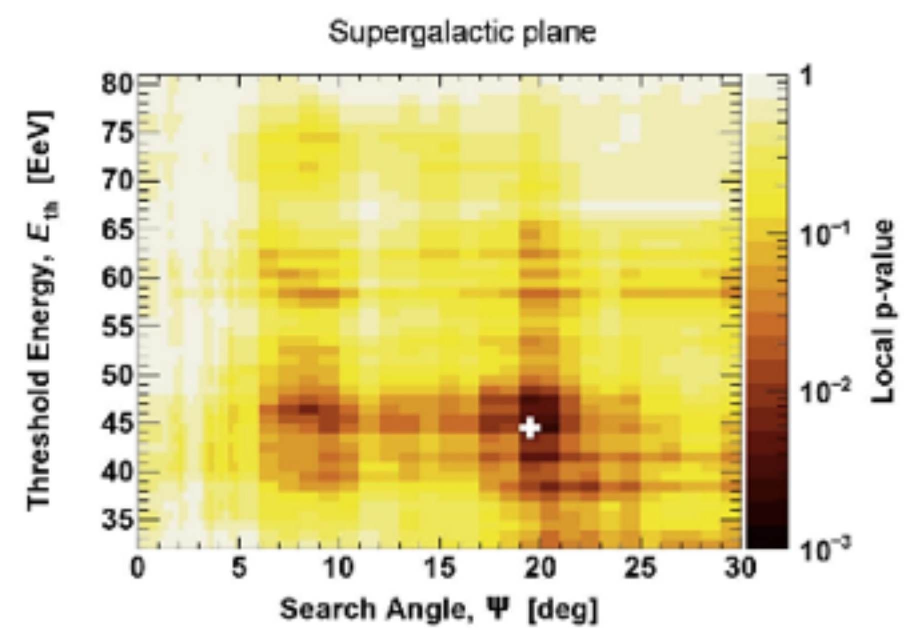
Pairs of events separated by given angular distance
Scan in threshold energy, angle Ψ



Search	E_{th} [EeV]	Angle, Ψ [deg]	N_{obs}	N_{exp}	Local p-value, f_{min}	Post-trial p-value
Autocorrelation	62	3.75	93	66.4	2.5×10^{-3}	0.24
Supergalactic plane	44	20	394	349.1	1.8×10^{-3}	0.13
Galactic plane	58	20	151	129.8	1.4×10^{-2}	0.44
Galactic center	63	18	17	10.1	2.6×10^{-2}	0.57

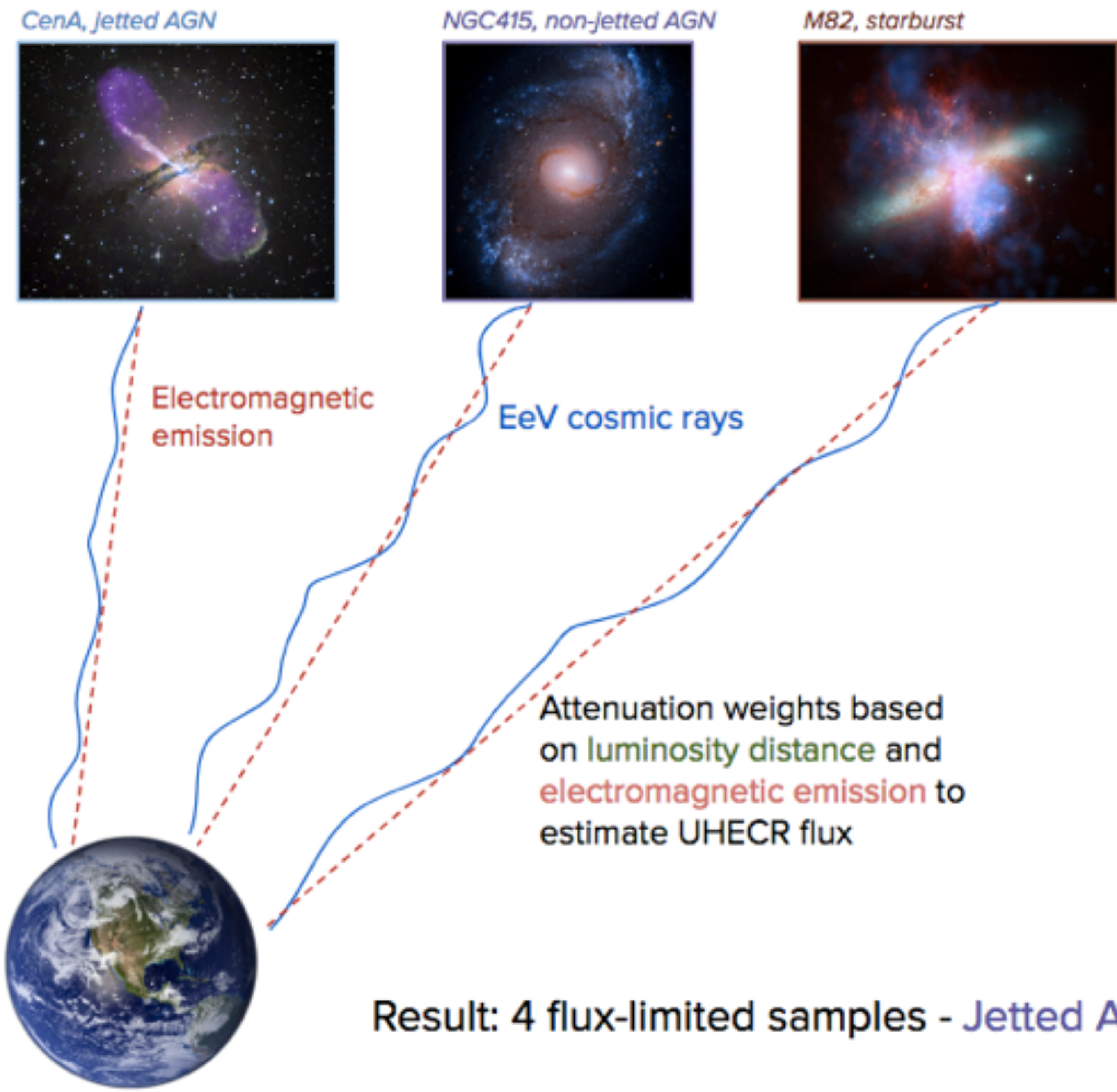




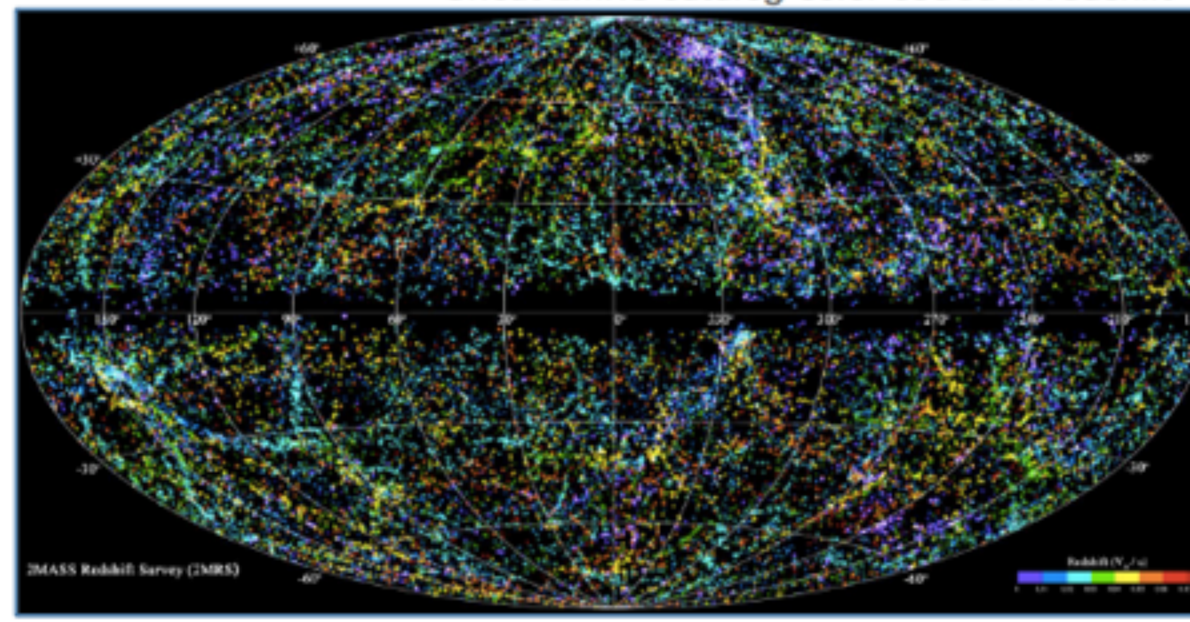


[ApJ 935 (2022)170]

Catalog-based correlations



Uncut 2MRS catalog color coded in redshift



AGN activity

Accretion = X-rays from SwiftBAT (523 galaxies at 14-195 keV)
Jet = γ-rays from 3FHL (26 galaxies at 10 GeV-1 TeV)

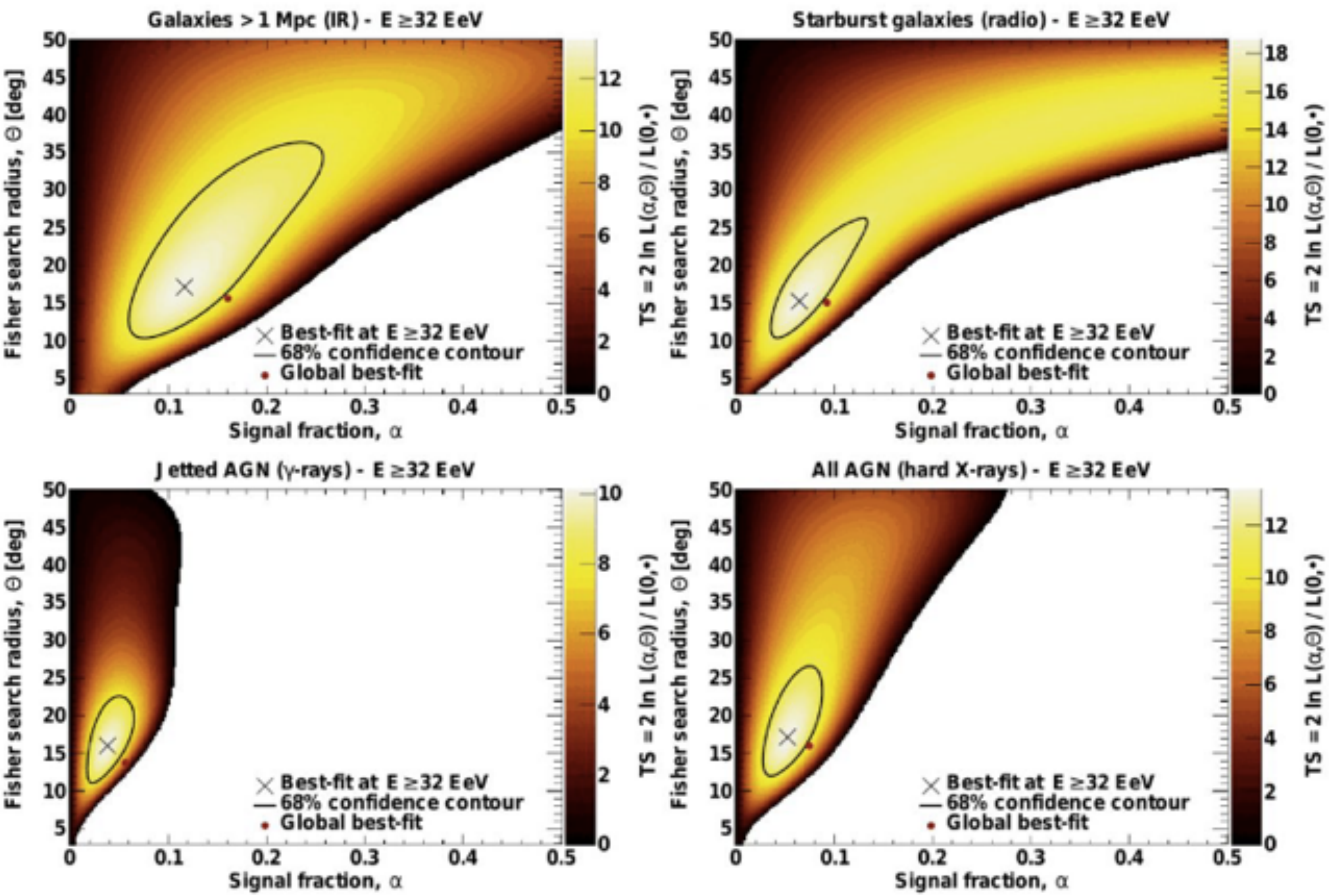
Star formation

Generic/**stellar mass = IR** from 2MRS (>40'000 galaxies 2.2 μm)
Burst = radio from Lunardini+19 (44 galaxies, 1.4 GHz)

Result: 4 flux-limited samples - Jetted AGNs, all AGNs, Starburst galaxies, all galaxies

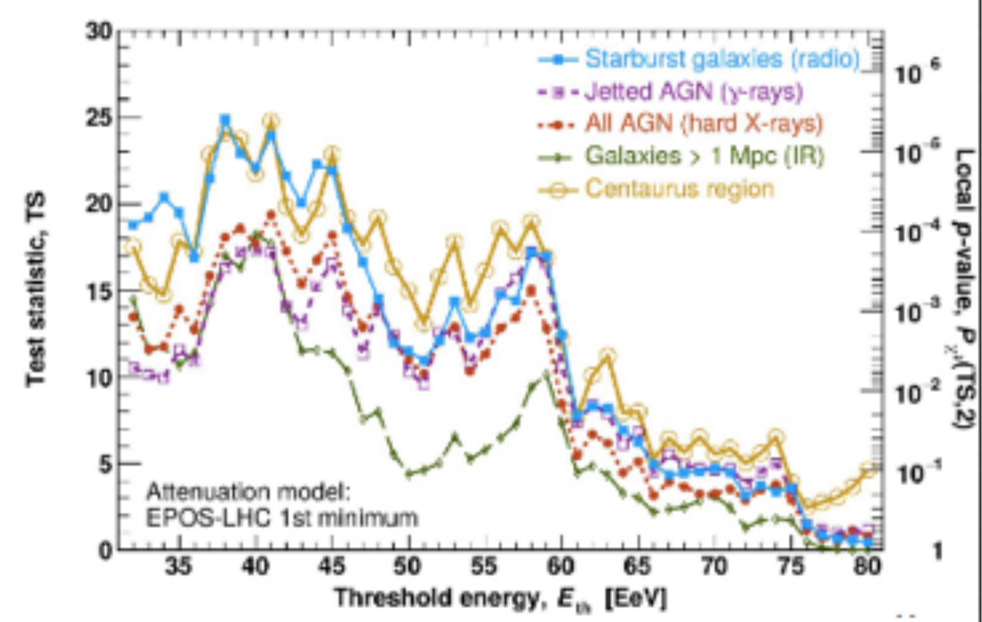
Catalog-based correlations

Fit of attenuated flux+isotropy
Variable signal fraction and smoothing scale



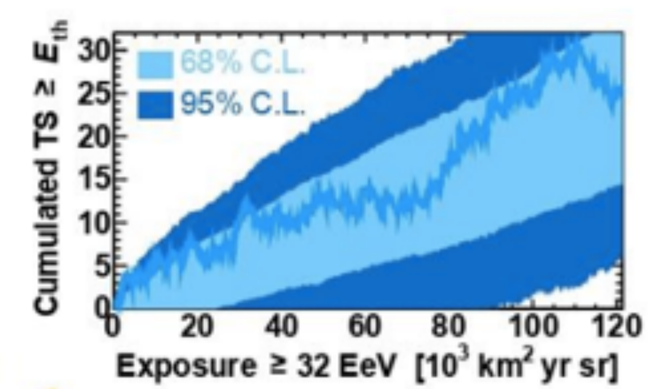
All catalogs have most significant signal at Eth=38-41 EeV, scale Ψ=23°-27°, signal fraction α=6-15%

Significance 3.1σ for jetted AGNs, **4.0σ for Starburst galaxies**



[ApJ 935 (2022)170]

SBG signal compatible with linear growth within the expected variance:



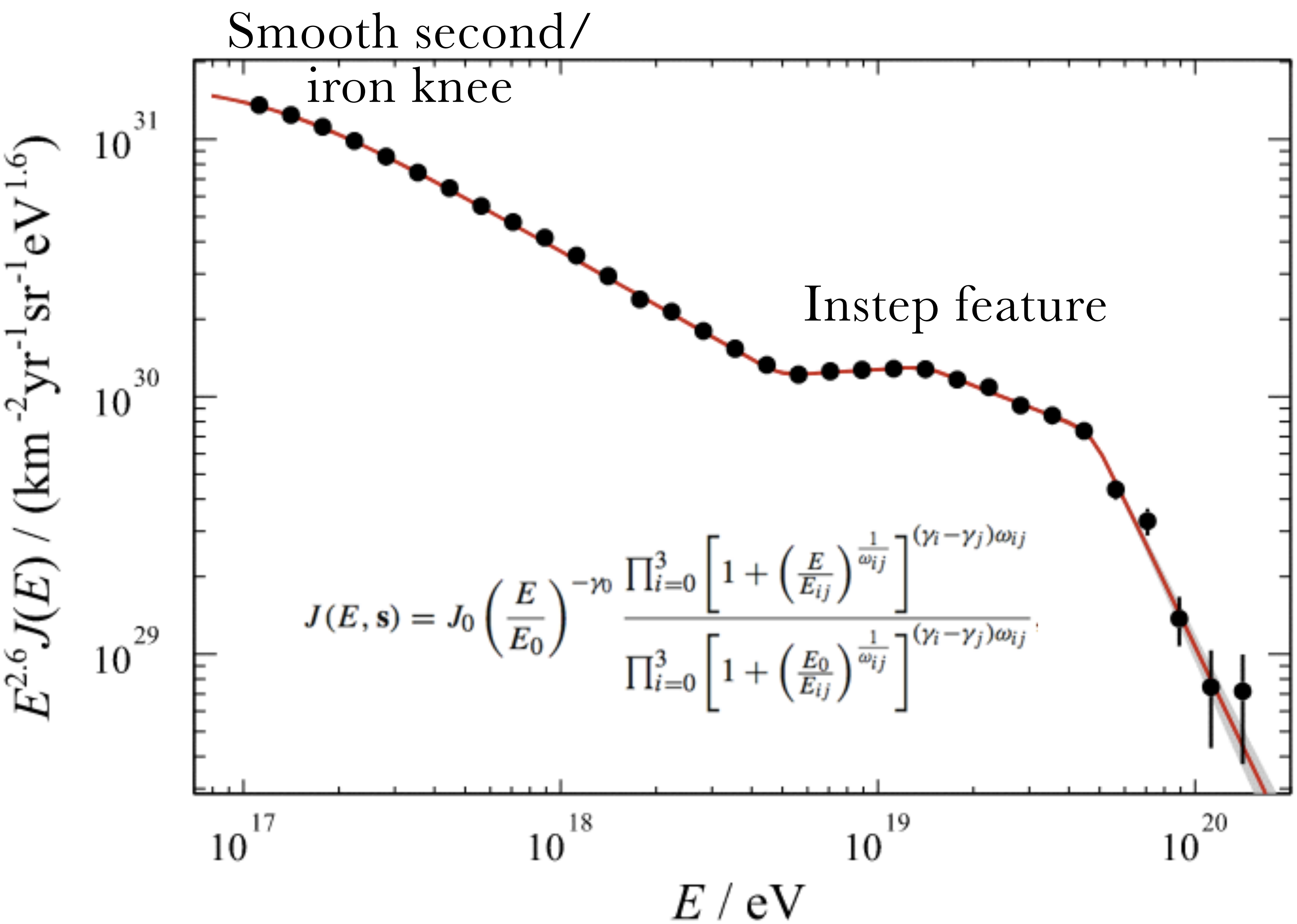
iii) Energy spectrum and mass composition: probing source properties

➡ Constraints on:

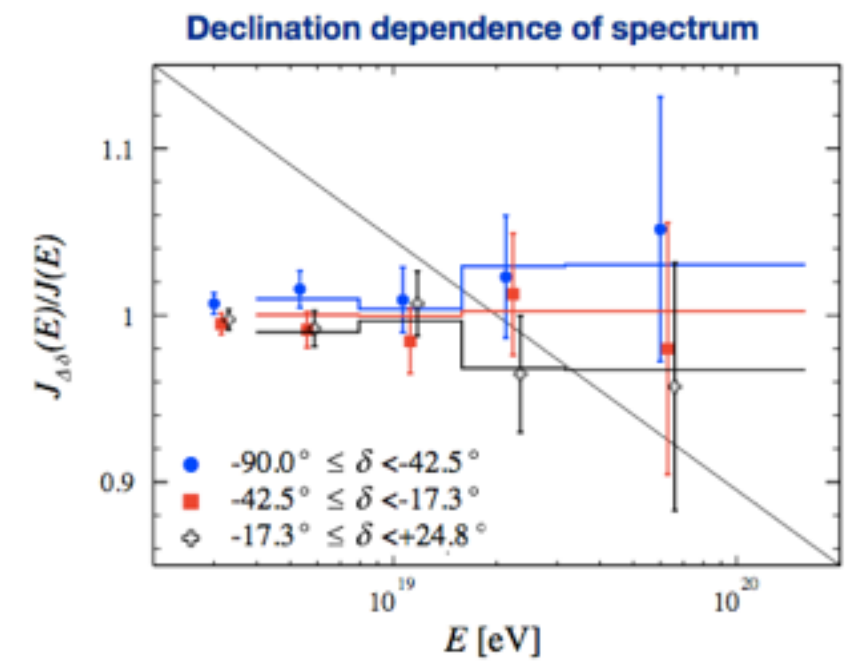
- acceleration/escape processes
- energetics of the sources
- abundances of elements in the source environments

Features in the energy spectrum > 10^{17} eV

[EPJC 81 (2021) 966]



[PRD 102 (2020) 062005]



Lines: Expectation from observed dipole

Parameter	Value $\pm\sigma_{stat}\pm\sigma_{syst}$
J_0 / (km^2 yr sr eV)	$(1.309 \pm 0.003 \pm 0.400) \times 10^{-18}$
ω_{01}	$0.43 \pm 0.04 \pm 0.34$
γ_1	$3.298 \pm 0.005 \pm 0.10$
E_{12}/eV	$(4.9 \pm 0.1 \pm 0.8) \times 10^{18}$
γ_2	$2.52 \pm 0.03 \pm 0.05$
E_{23}/eV	$(1.4 \pm 0.1 \pm 0.2) \times 10^{19}$
γ_3	$3.08 \pm 0.05 \pm 0.10$
E_{34}/eV	$(4.7 \pm 0.3 \pm 0.6) \times 10^{19}$
γ_4	$5.2 \pm 0.2 \pm 0.1$
γ_0	2.64 – fixed
E_{01}/eV	1.24×10^{17} – fixed
ω_{12}	0.05 – fixed
ω_{23}	0.05 – fixed
ω_{34}	0.05 – fixed

Measurements of the depth of shower maximum X_{max}

47863 high-quality events

1020 events with $E > 10$ EeV

the highest energy 104 ± 9.5 EeV

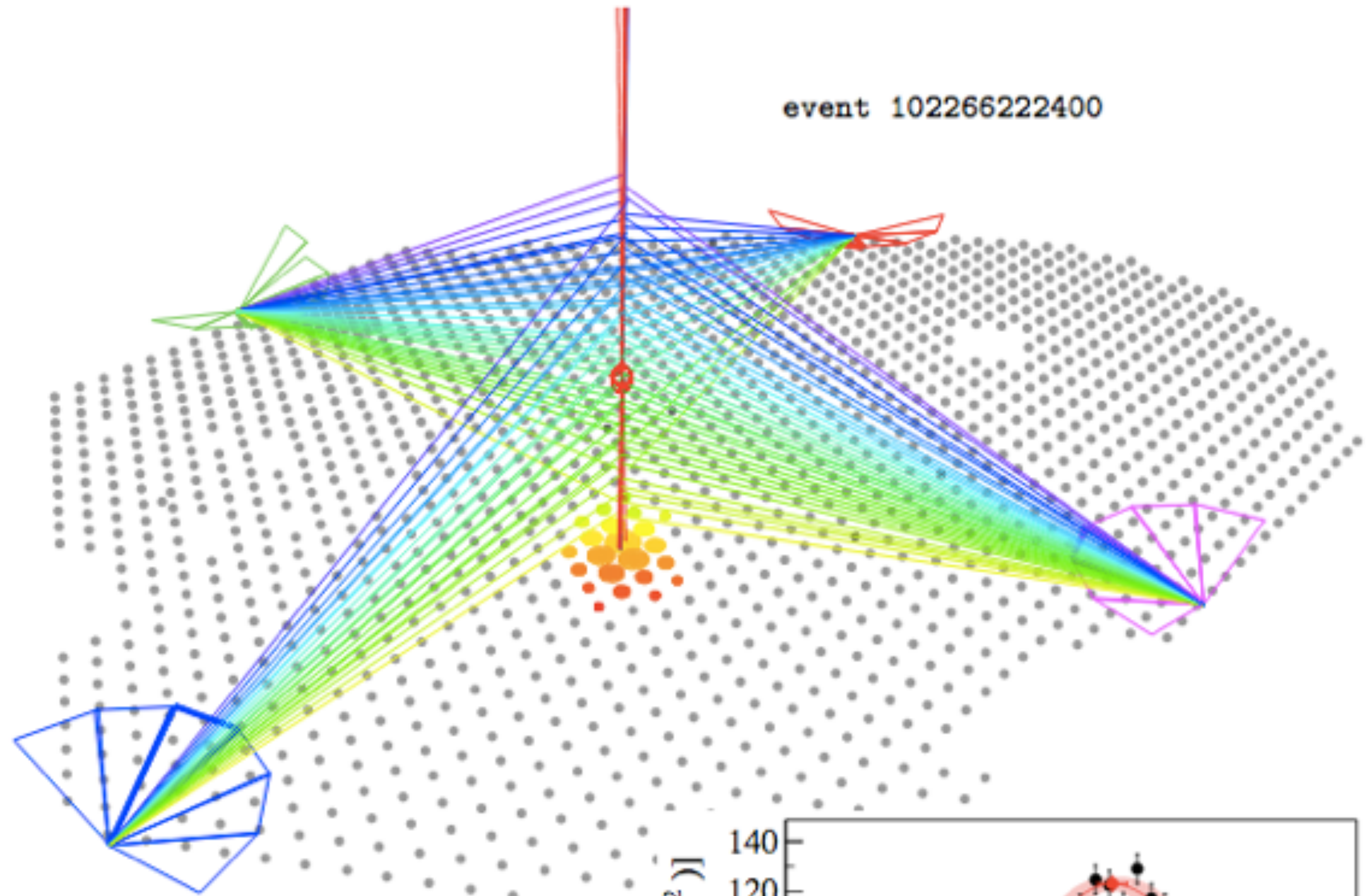
systematics $\lesssim 10\ \mathrm{g\,cm^{-2}}$

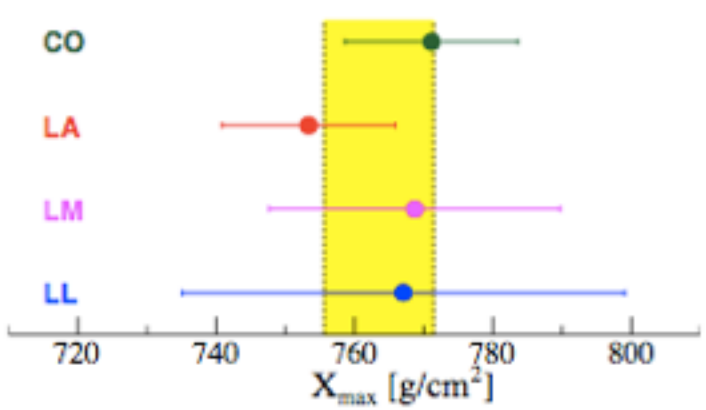
resolution

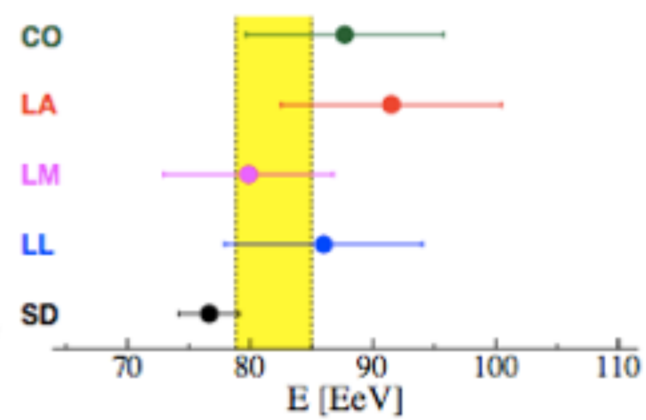
$40\ \mathrm{g\,cm^{-2}}$ at $10^{17.2}$ eV

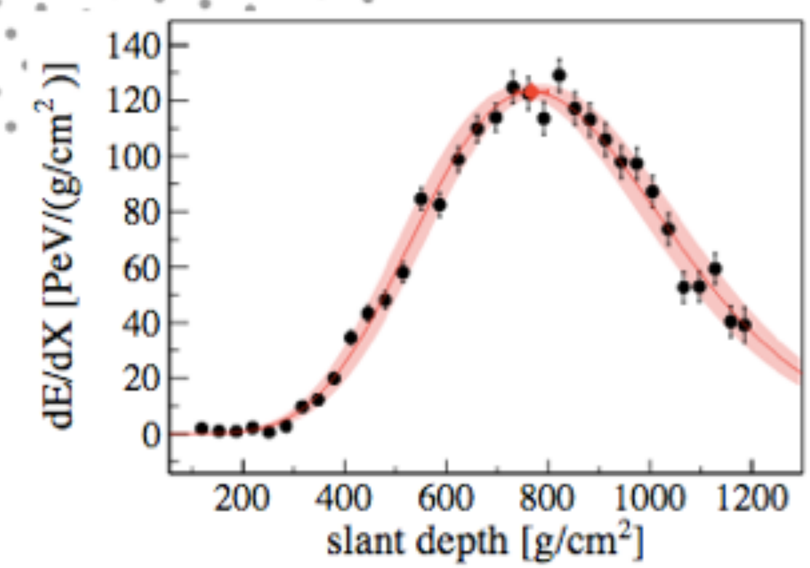
$25\ \mathrm{g\,cm^{-2}}$ at $10^{17.8}$ eV

$15\ \mathrm{g\,cm^{-2}}$ for $E > 10^{19.0}$ eV







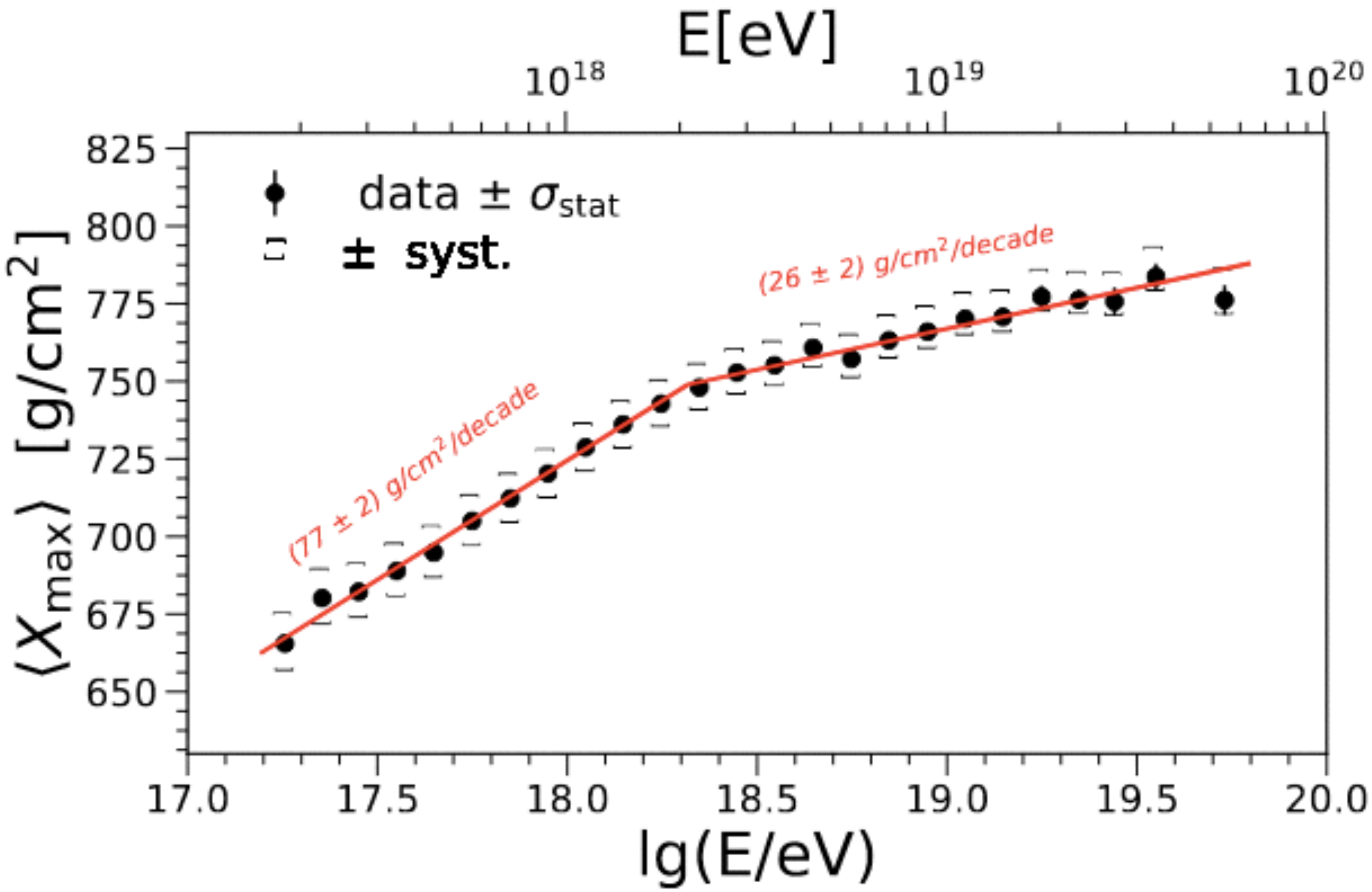


Rate of change of $X_{\max}$ with energy

One of the most reliable observables for mass composition analysis

simulations: ≈ 60 [g cm^{-2}/decade] for constant compositions

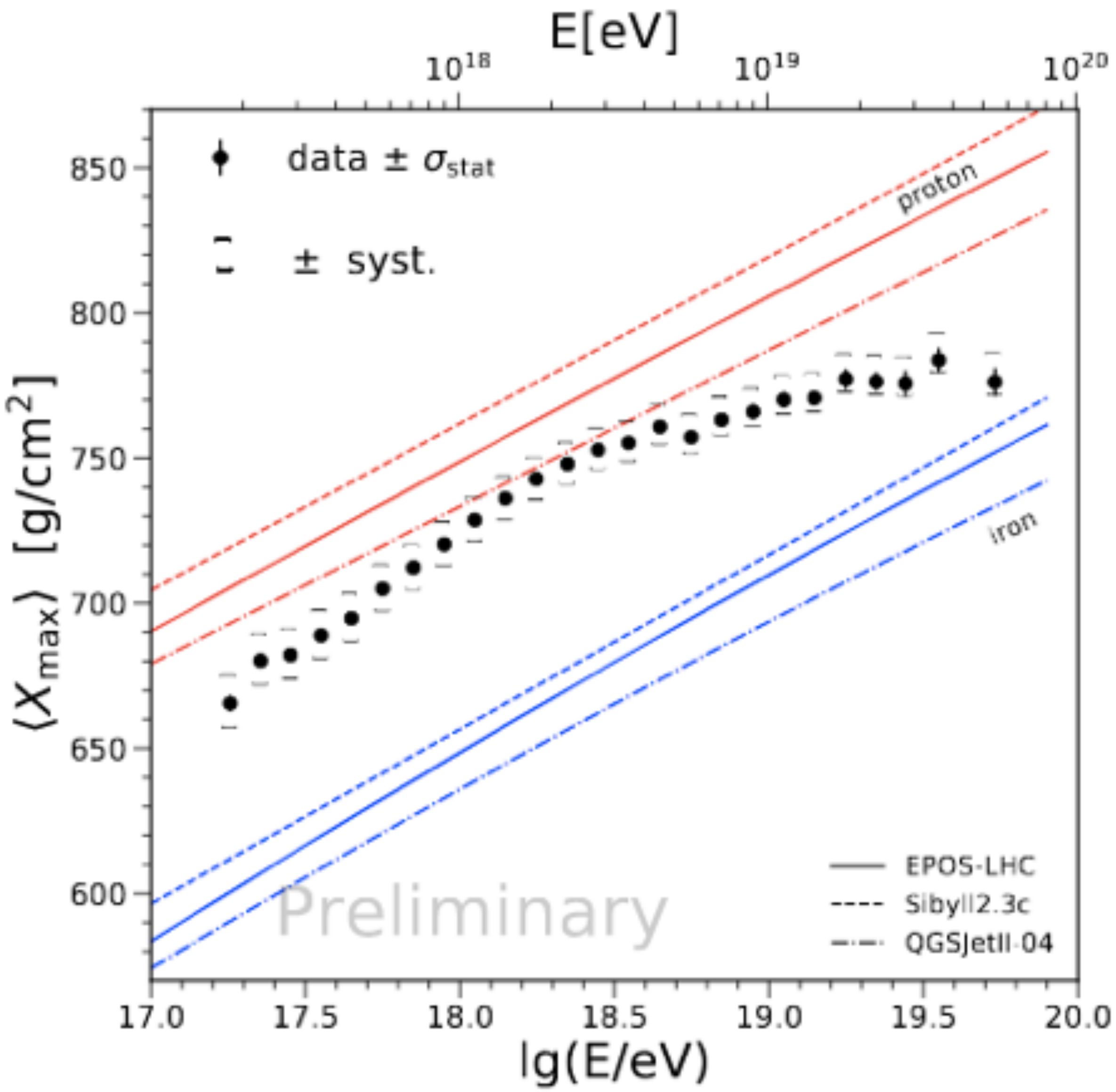
[Yuchkov, ICRC2021]

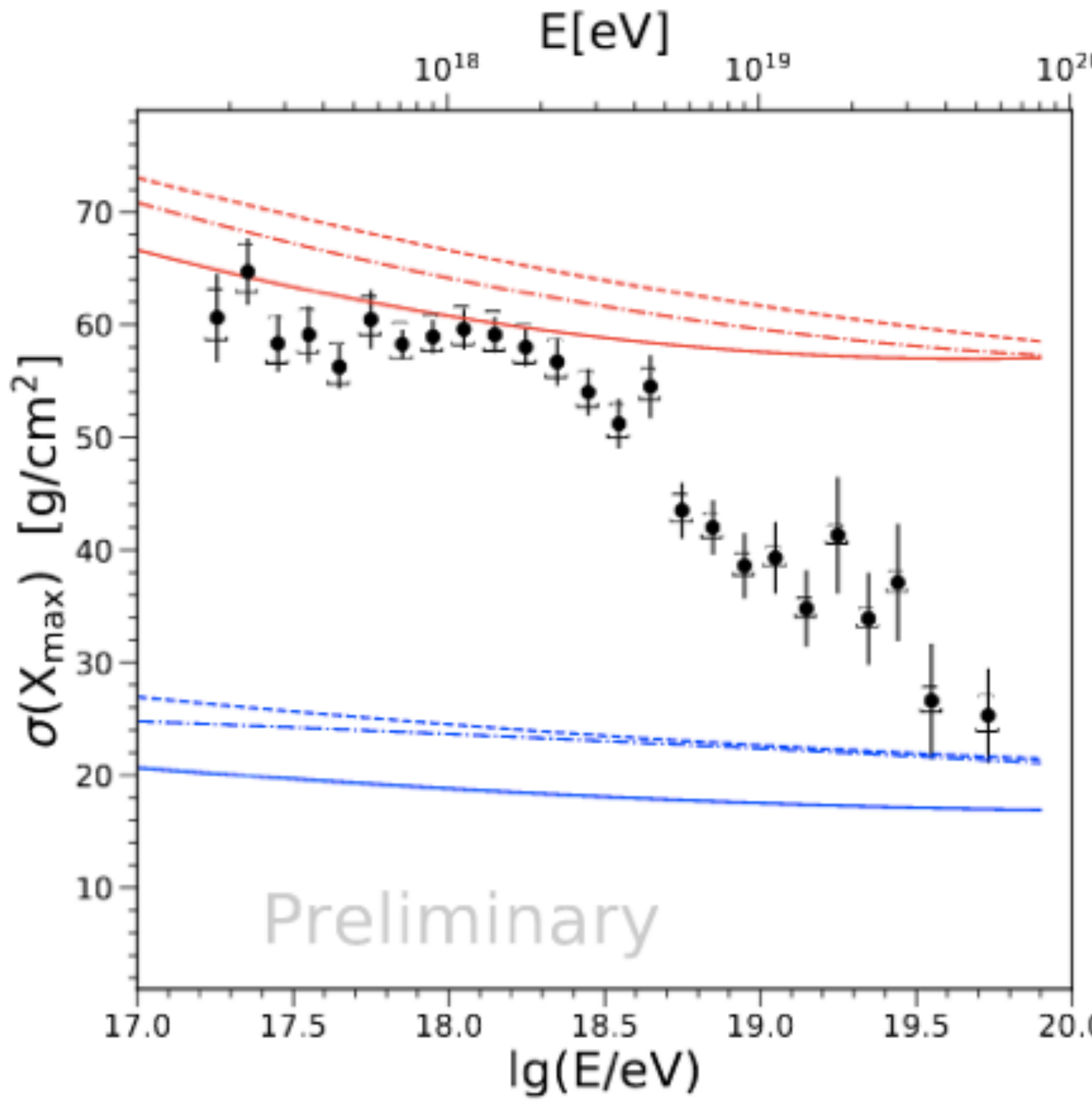


Composition is getting lighter below $E_0 \approx 2$ EeV and heavier afterwards

$X_{\max}$ moments: data vs simulations

Above $E_0 \approx$ 2 EeV both $X_{\max}$ moments are becoming compatible to MC predictions for heavier nuclei

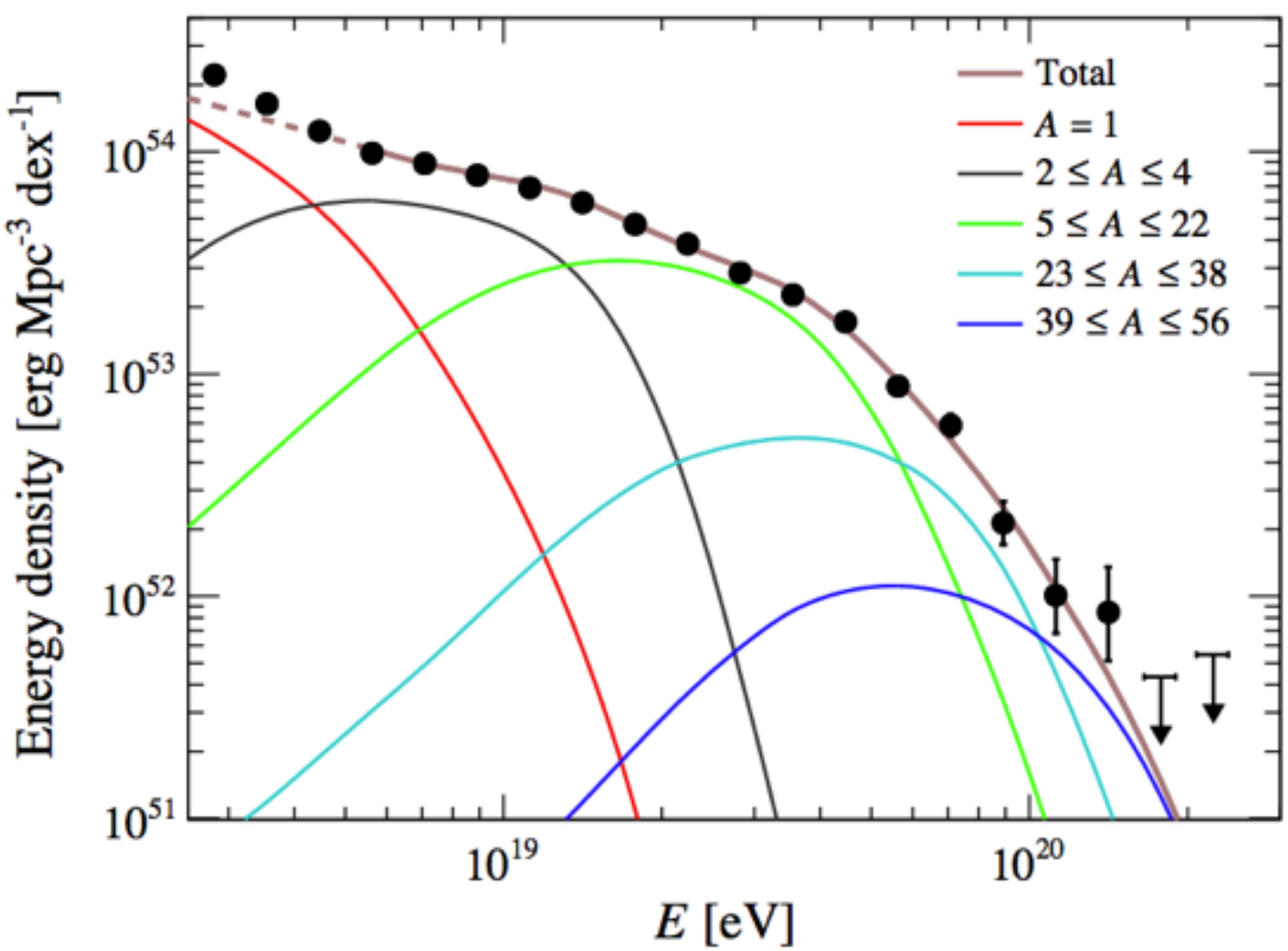




[Yuchkov, ICRC2021]

Astrophysical picture

[PRL 125 (2020) 121106]

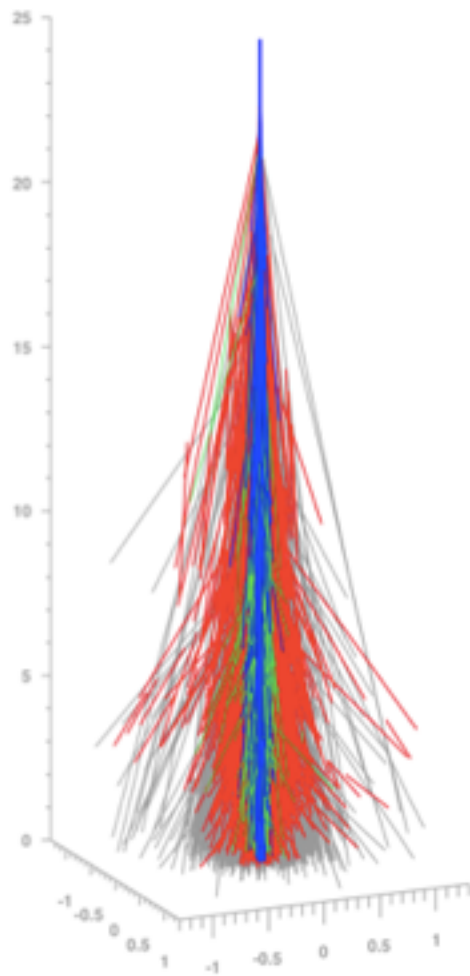


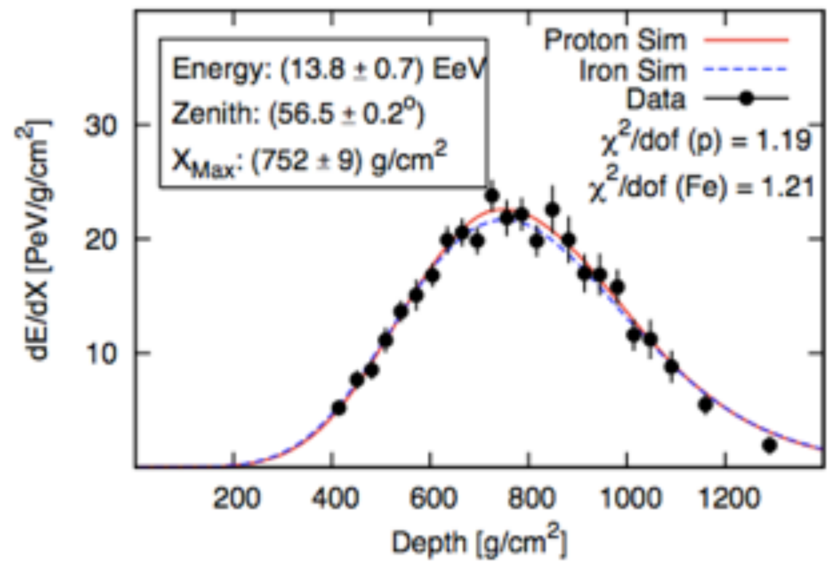
- ✦ Hard ejected spectra (quasi mono-elemental fluxes at UHE)
- ✦ Energy cutoff ~5Z EeV
- ✦ Steepening above ~50 EeV: combination of the maximum energy of acceleration of the heaviest nuclei at the sources and the GZK effect
- ✦ Steepening above ~10 EeV: interplay between the flux contributions of He and CNO injected at the source with their distinct cutoff energies, shaped by photodisintegration during the propagation
- ✦ Luminosity density ($E^2 q_{\rm gen}(E)$): 6 10^{44} erg Mpc^{-3} yr^{-1}

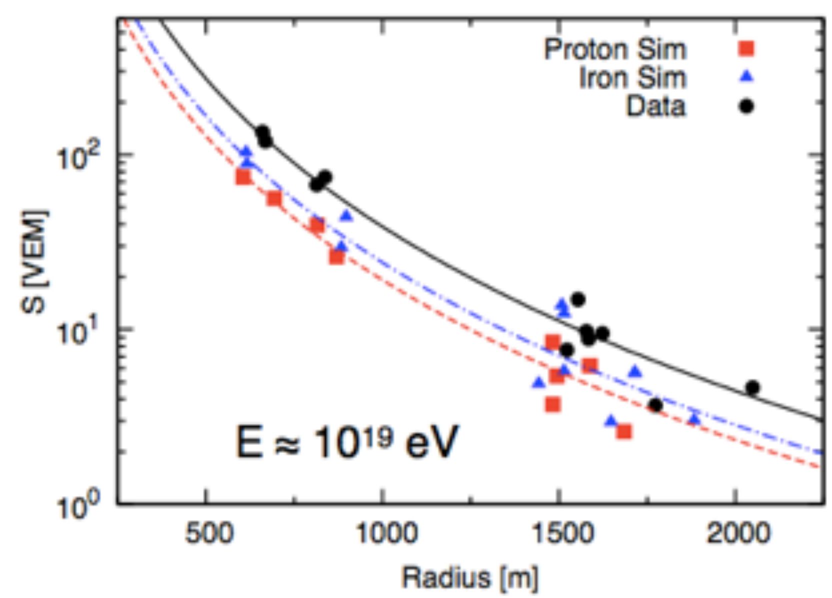
iv) Puzzles in extensive air showers

« The subject of cosmic rays is unique in modern physics for the minuteness of the phenomena, the delicacy of the observations, the adventurous excursions of the observers, the subtlety of the analysis, the grandeur of the inferences » **B. Rossi**

Comparison of longitudinal and lateral shower profiles



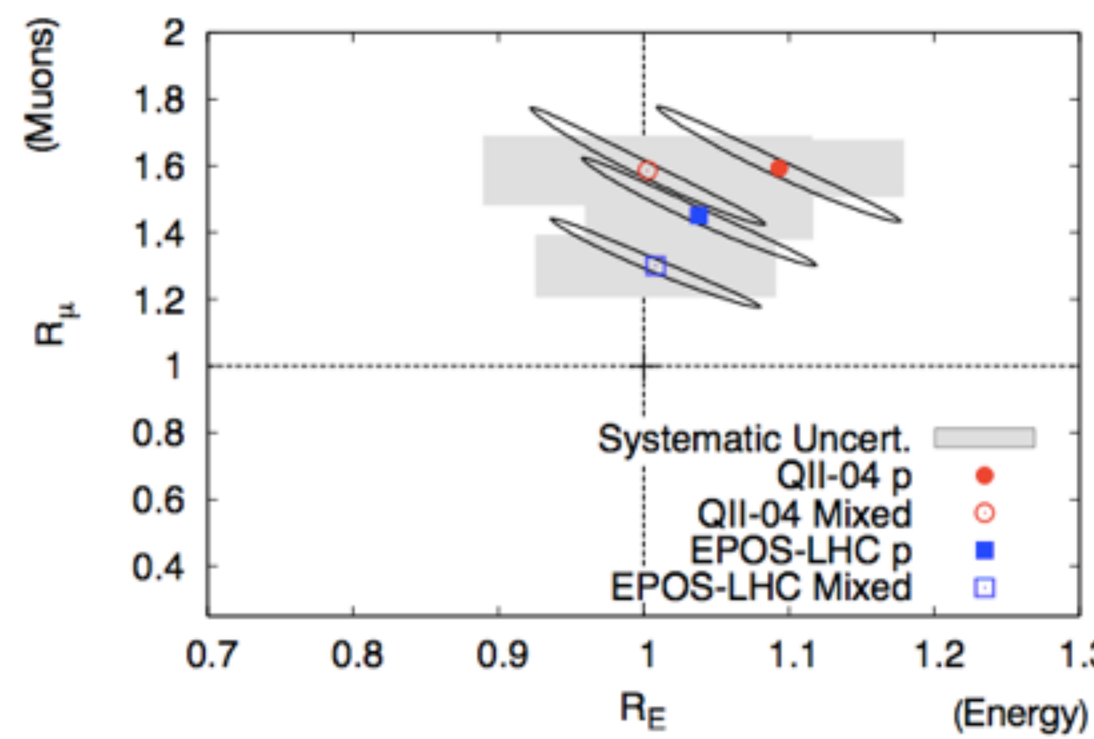




Phenomenological model ansatz

Energy scaling: em. particles and muons

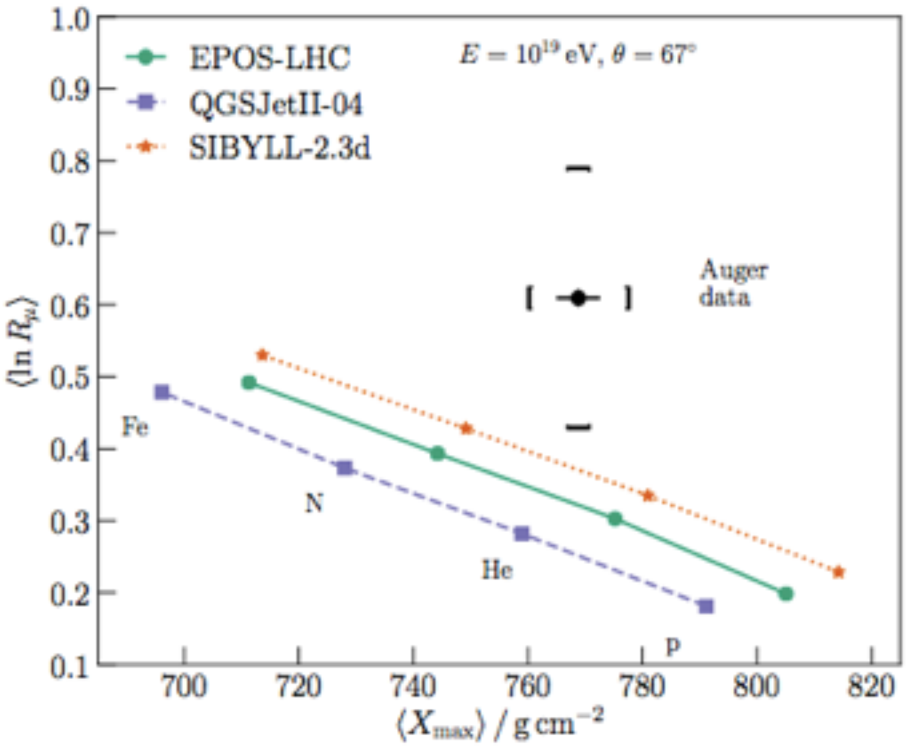
Muon scaling: hadronically produced muons and muon interaction/decay products



[PRL, 117 (2016) 192001]

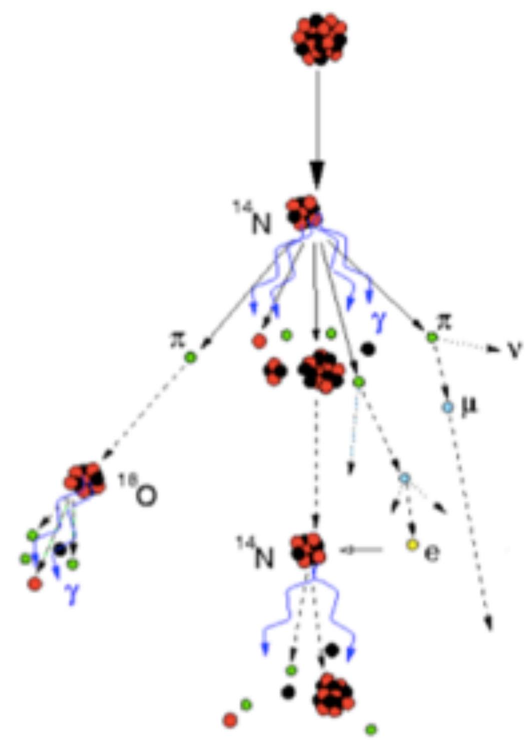
Muon number in inclined showers (θ > 60°)

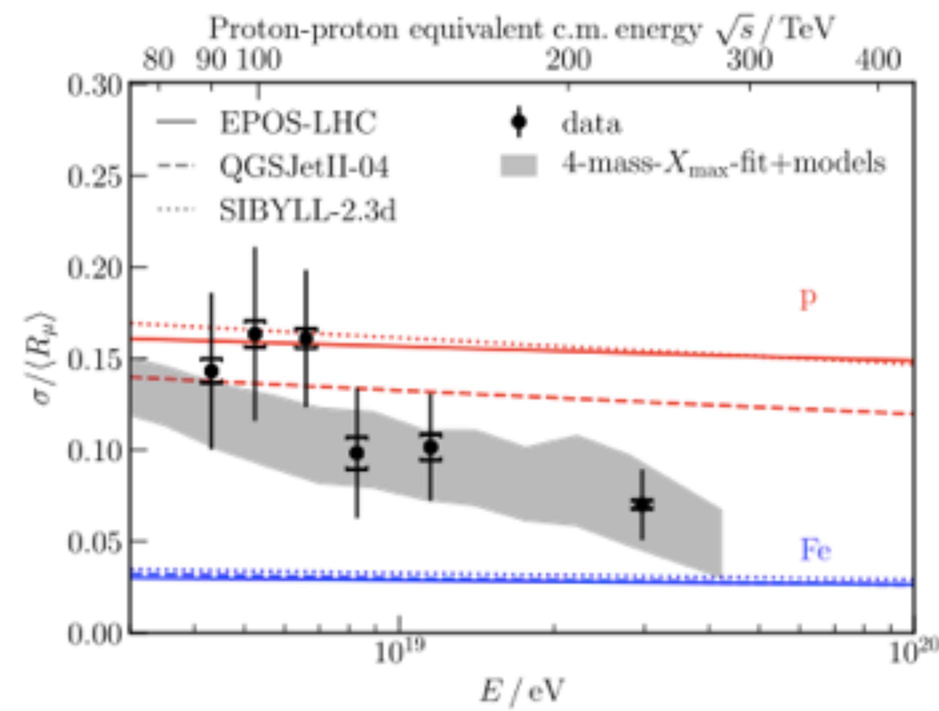
[PRL, 126 (2021) 152002]



[PRD, 91 (2015) 032003]

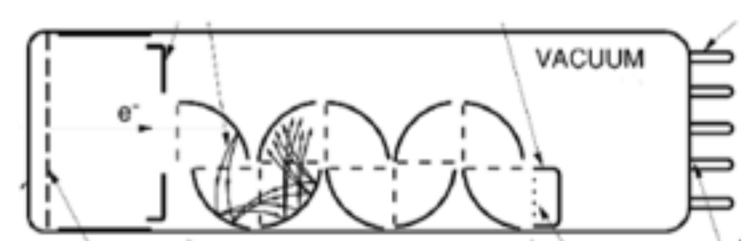
Hybrid events and inclined showers





Discrepancy in number of muons
Relative fluctuations as expected

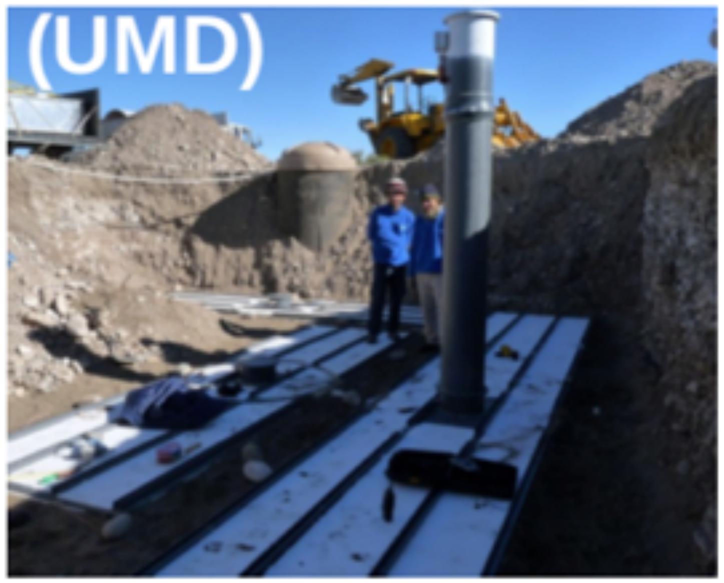
PMT analogy of air shower



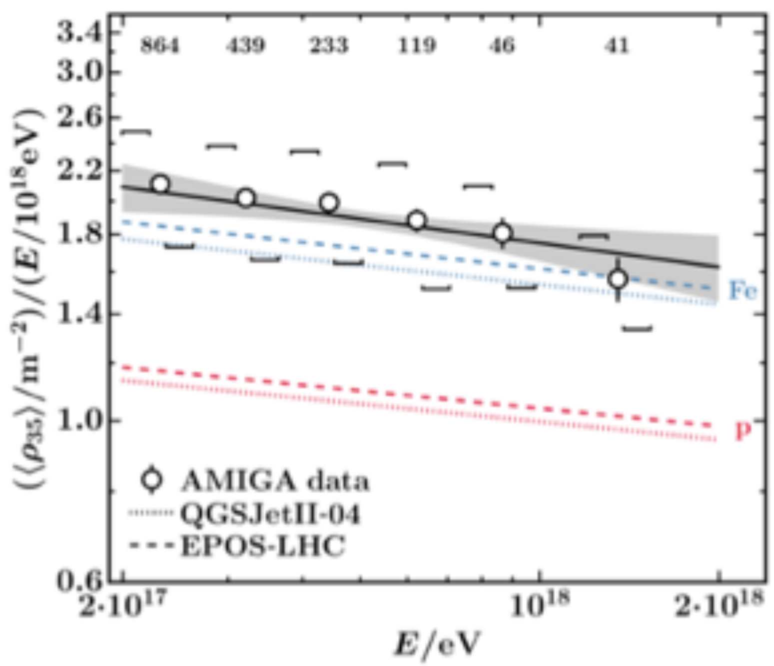
Muon fluctuations driven by first interactions

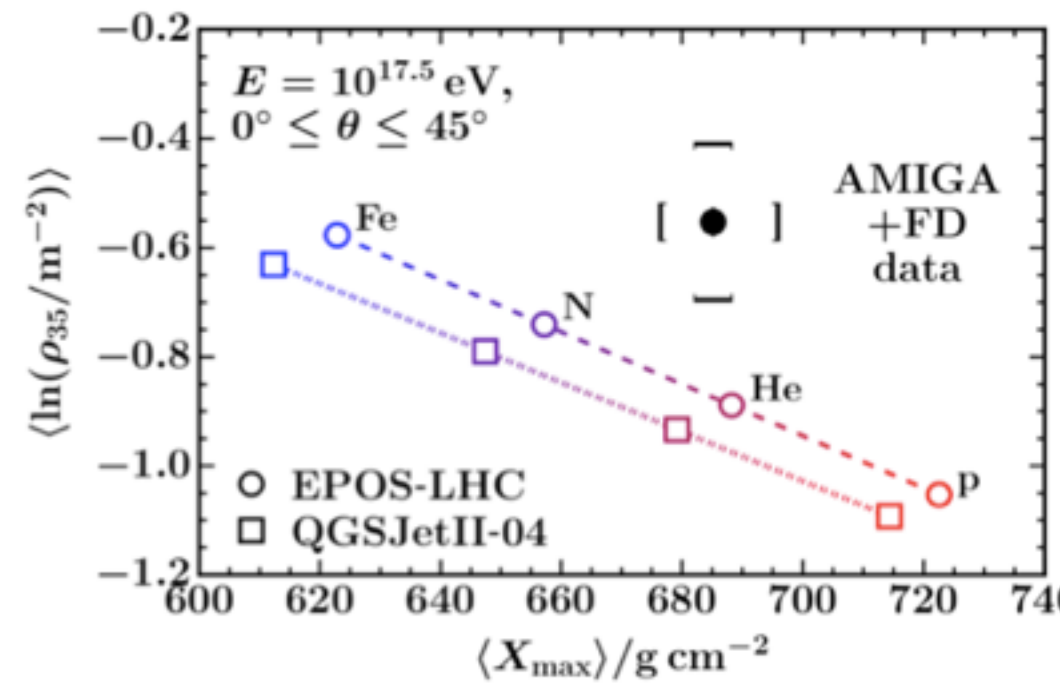
Direct measurement of muons at lower energy

[EPJC, 80 (2020) 751]



Underground muon detectors
(2.3 m soil for shielding)

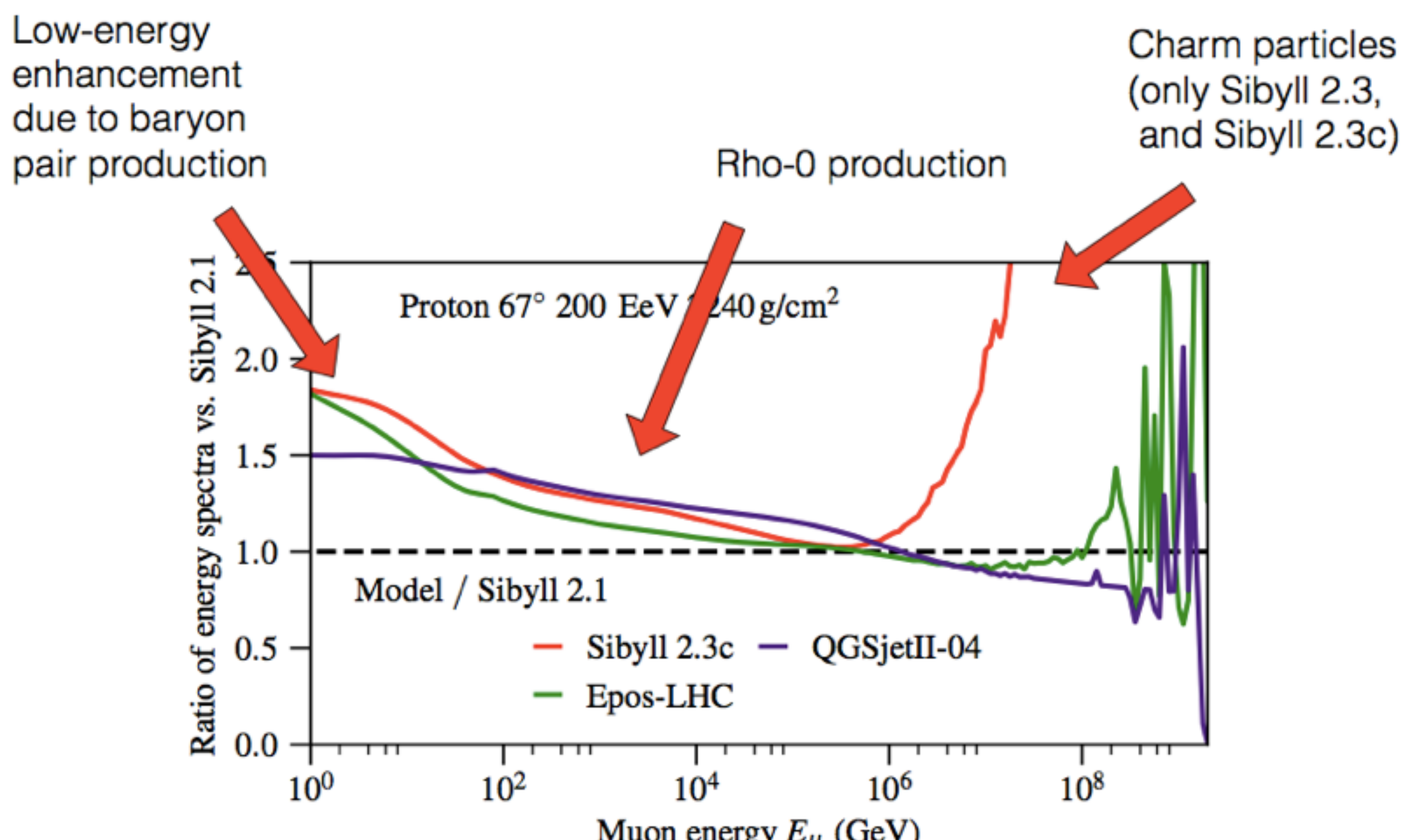




In range $3\mathrm{x}10^{17}$ eV to $2\mathrm{x}10^{18}$ eV simulations don't reproduce muon densities
38% (53%) increase in $<N_{\mu}>$ at 10^{18} eV needed for EPOS-LHC (QGSJetII-04)

Muon production in hadronic showers

Muon energy spectrum in EAS relative to that of Sibyll 2.1



[Courtesy, R. Engel]

v) Photons, neutrinos, (super-heavy) dark matter

« Une fourmi parlant français
Parlant latin et javanais
Ça n'existe pas ça n'existe pas
Et pourquoi pas ? » **R. Desnos**

Why searching for SHDM?

- Concordance model in cosmology: no interaction between SM and DM sectors
- Most of DM models: concordance model slightly wrong to make the dark sector (slightly) observable through the weak interaction or a new feeble one
- What if the concordance model is exact in the sense that gravitation is the only portal?
- Abundance of DM produced during reheating matching the relic abundance observed today for some combinations of H_{inf}, T_{reh}, and for M_X quite large

[Garny et al. PRL 116 (2016) 101302,

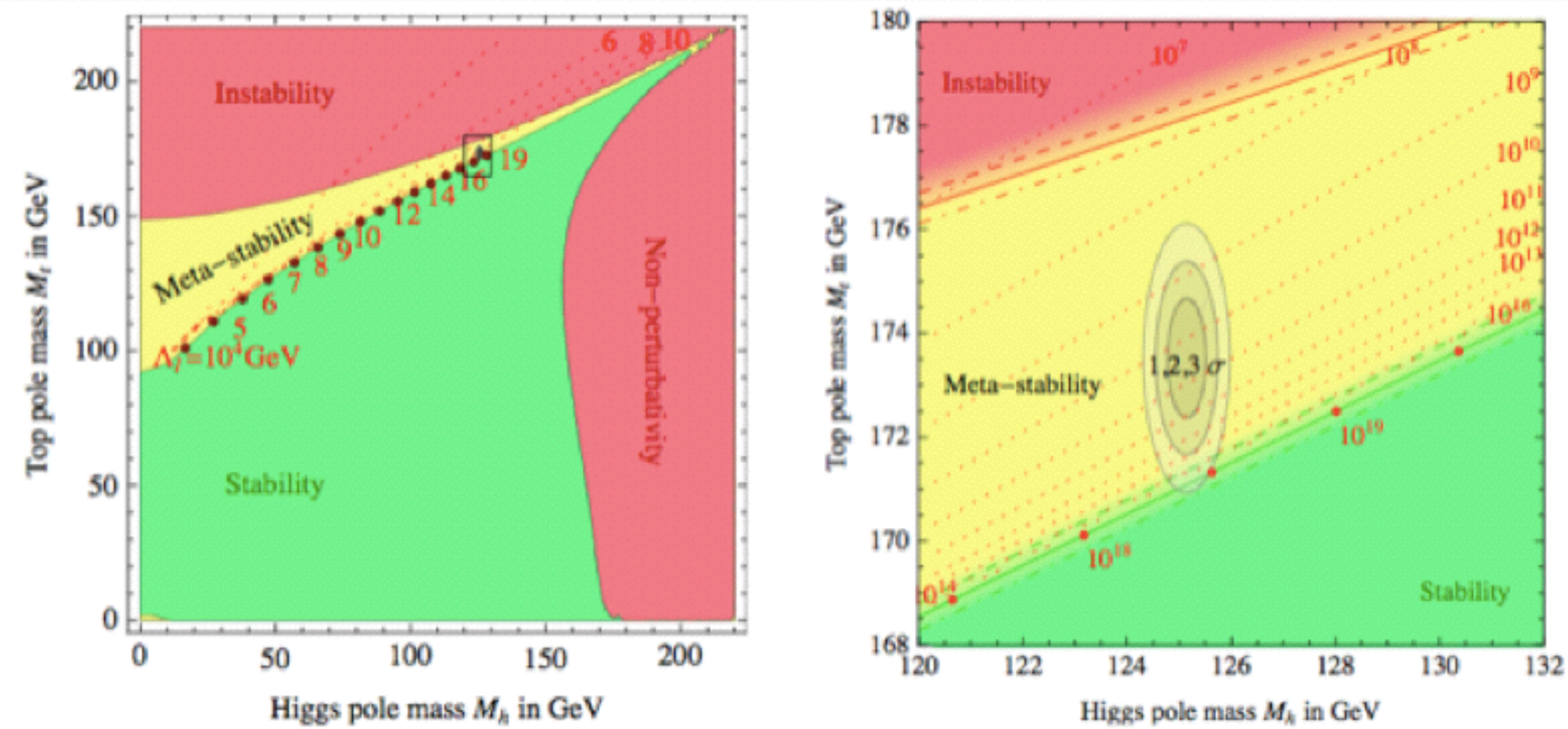
Mambrini & Olive PRD 103 (2021) 11, 115009]

- No new physics at LHC: problem of the Higgs mass not solved by naturalness?
- Precision measurements of m_{H} and m_{top} allowing for inferring a very high instability energy scale

LHC SM phase diagrams

- Extrapolation of the SM parameters up to large energies with full 3-loop NNLO precision

D. Buttazzo et al., JHEP vol 2013, 89 (2013)



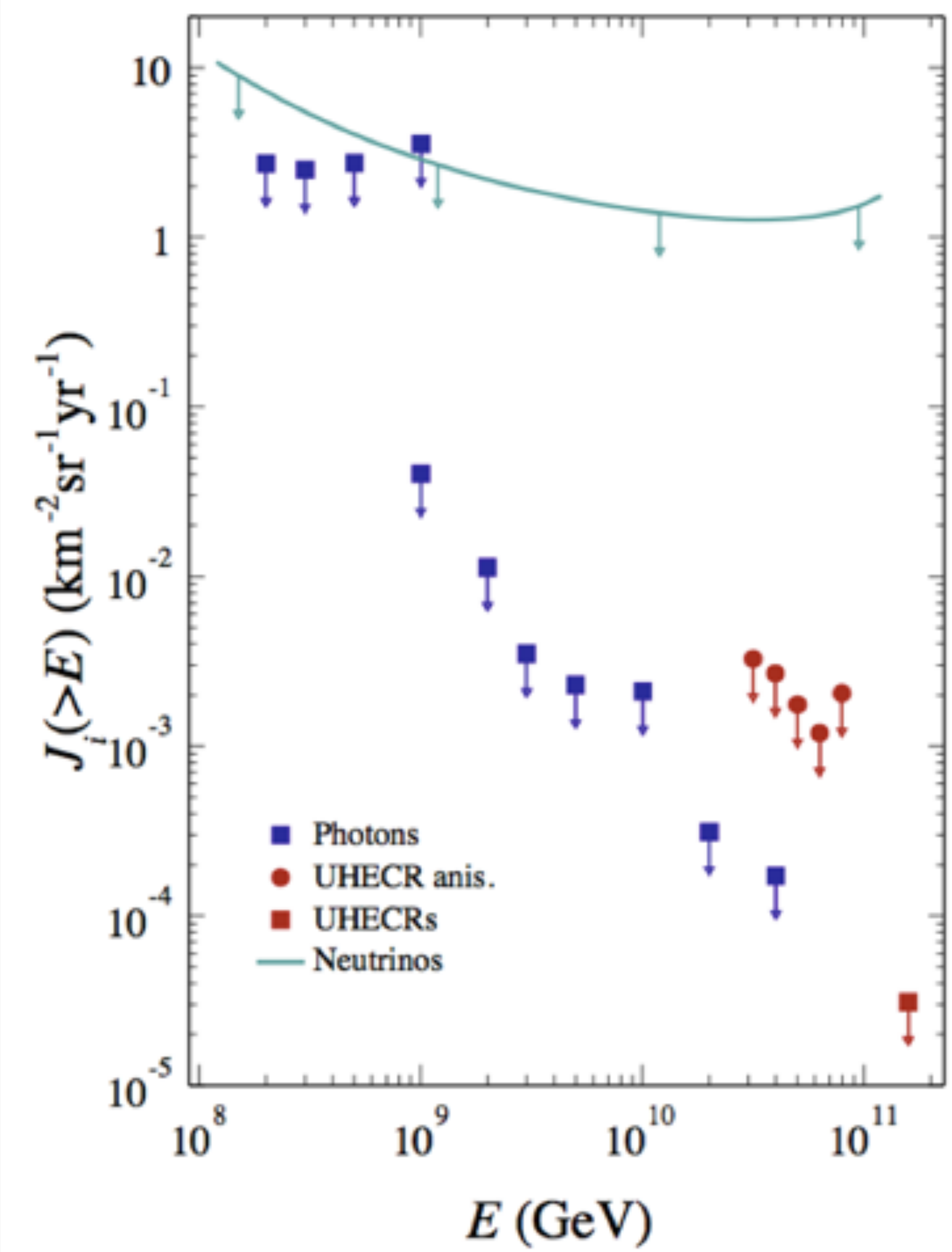
- Precise values of Higgs boson mass + top Yukawa coupling $\Longrightarrow$ SM vacuum *meta-stable* up to high Λ

Secondary by-product fluxes from SDHM decay

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

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

- $\rho_{\rm DM}$: DM profile
- $\frac{\mathrm{d}N_i}{\mathrm{d}E}$: energy spectra of $i = \gamma, \nu, \overline{\nu}, N, \overline{N}$ from hadronization processes, evolving the fragmentation functions from EW scale up to M_X using DGLAP [Aloisio et al., Phys. Rev. D 69 094023 (2004)] here, see also Sarkar & Toldra (2002), Barbot & Drees (2003), Kachelriess et al. (2018), Alcantara, et al. (2019)
- Free parameters: M_X, τ_X

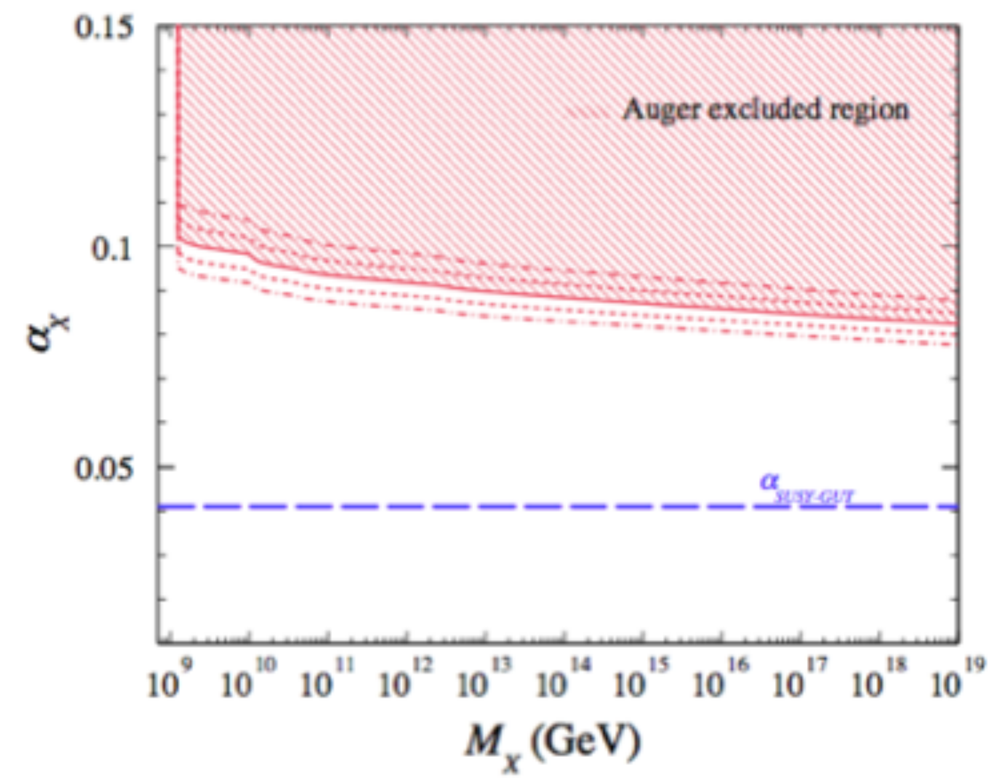


Constraints on non-perturbative decay

[Kuzmin & Rubakov, Phys. Atom. Nucl.979 61, 1028 (1998)]

- SHDM particles protected from standard decay by perturbative effects through a new quantum number
- Still, non-perturbative effects can lead to decays through "instantons" in non-commutative gauge theories
- For *B*, *L* and *X* currents not associated to gauge interactions, possibility to exchange quantum numbers through an anomaly

- Lifetime of metastable *X* particles: $\tau_X \simeq M_X^{-1} \exp\left(4\pi/\alpha_X\right)$ [t'Hooft, PRL 37 (1976) 8]

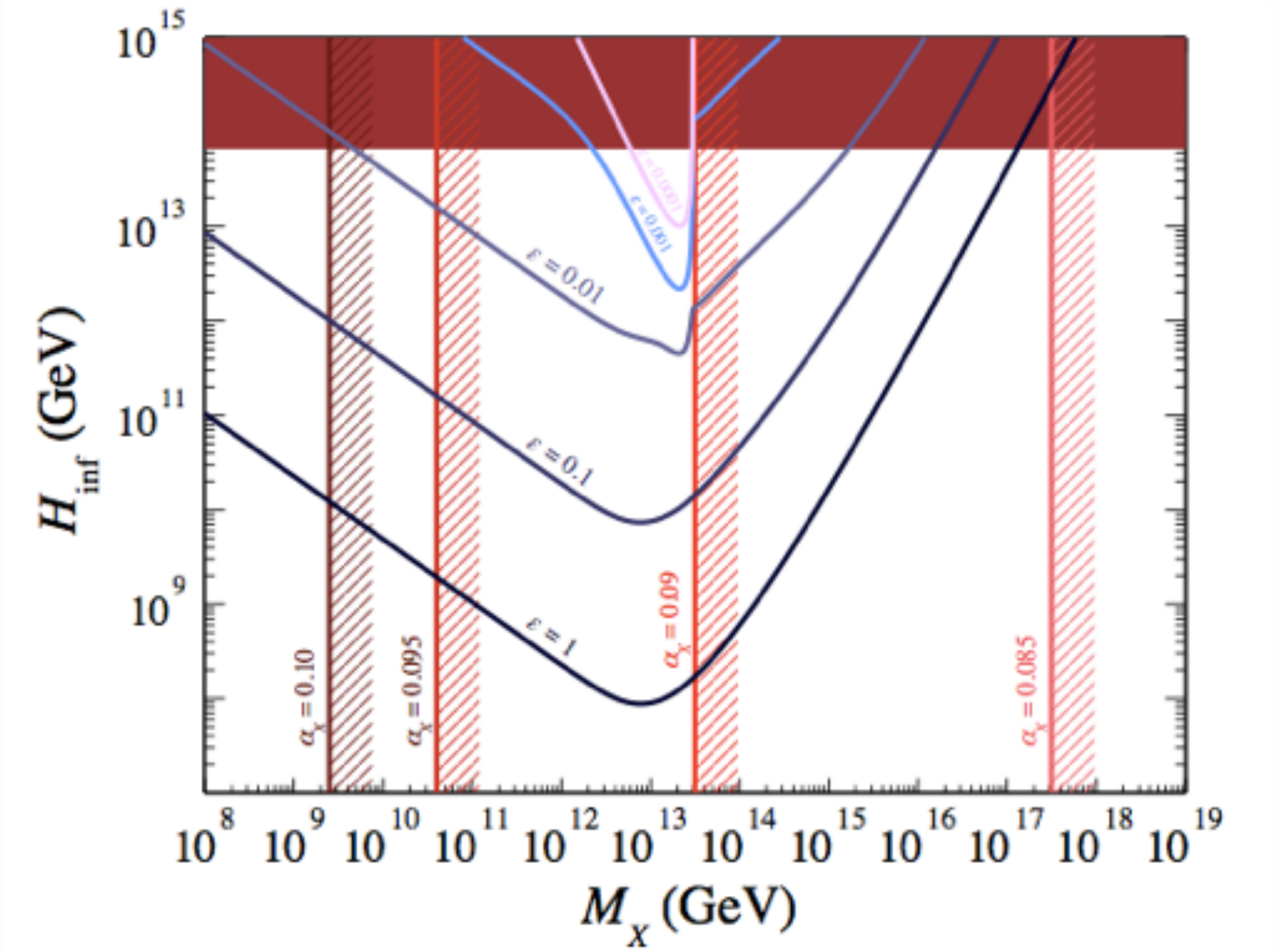


[arXiv:2203.08854, arXiv:2208.02353]

Non-thermal SHDM production during reheating

- Delineating viable regions in the $(H_{\rm inf}, M_X)$ plane for various ϵ values to match the DM relic density

[arXiv:2203.08854, arXiv:2208.02353]



- GUT mass scale viable for $\epsilon \to 1$ ($T_{\rm rh}$ relatively high) $\Longrightarrow$ tensor/scalar ratio r of the primordial modes possibly detectable in the CMB
- For $\epsilon \le 0.01$, 10^{13} GeV mass scale viable, testable for $\alpha_X \lesssim 0.09$

All the rest…

- Multi-messenger implications [V. Novotny's talk]
- Upgrade of the Observatory [T. Suomijärvi's talk]
- Outreach [R. Sarmento's talk]
- Open data [P. Ghia's talk]

- Atmospheric electricity phenomena (ELVES, TGFs, …)
- Radio-detection of EAS
- X_{max} estimations from SD (risetime, DNN, etc.)
- Dependences of $\langle X_{\mathrm{max}} \rangle$ in arrival directions
- p-air and p-p cross section
- Muon production depth
- Modification of hadronic interaction models
- Constraints on Lorentz invariance violation
- Searches for ANITA-like anomalous events
- Low-energy extensions below 10^{17} eV
- Common studies with TA
- …

Extragalactic gamma-ray sources

3FHL catalog
(*Fermi*-LAT, >50 GeV, < 250 Mpc)
[Ackermann *et al.*, 2016]

(leptonic processes preferred)

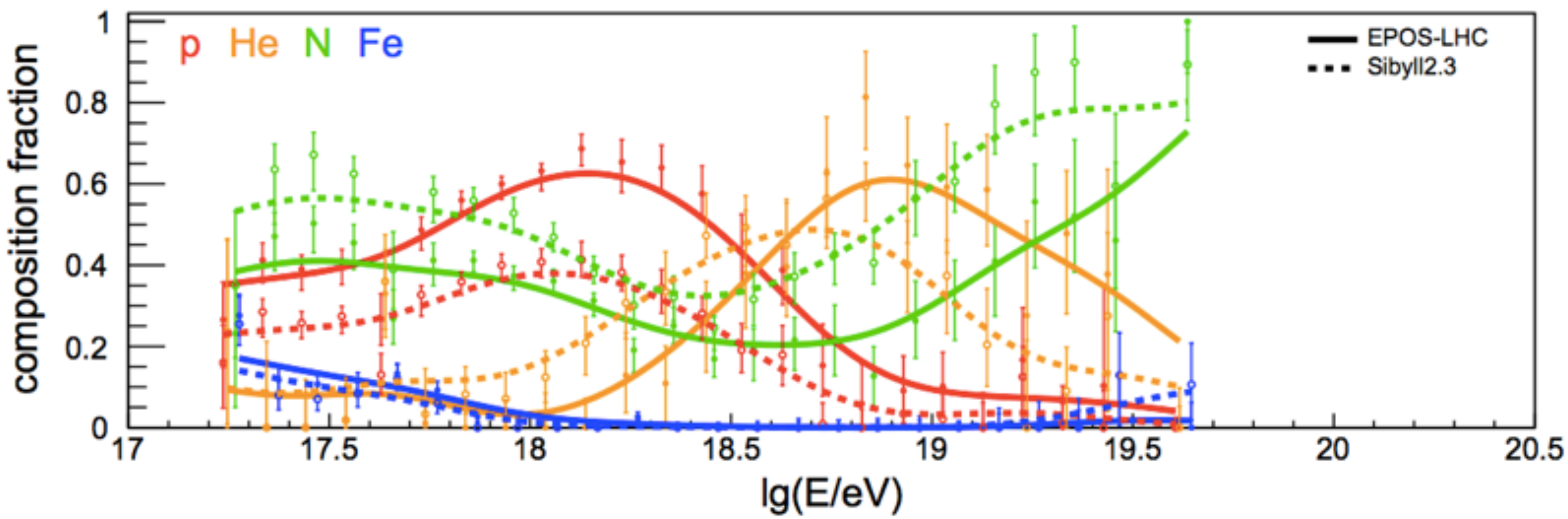
Selection by *Fermi*-LAT
(HCN survey) < 250 Mpc,
flux radio>0.3 Jy [Gao & Salomon, 2005]

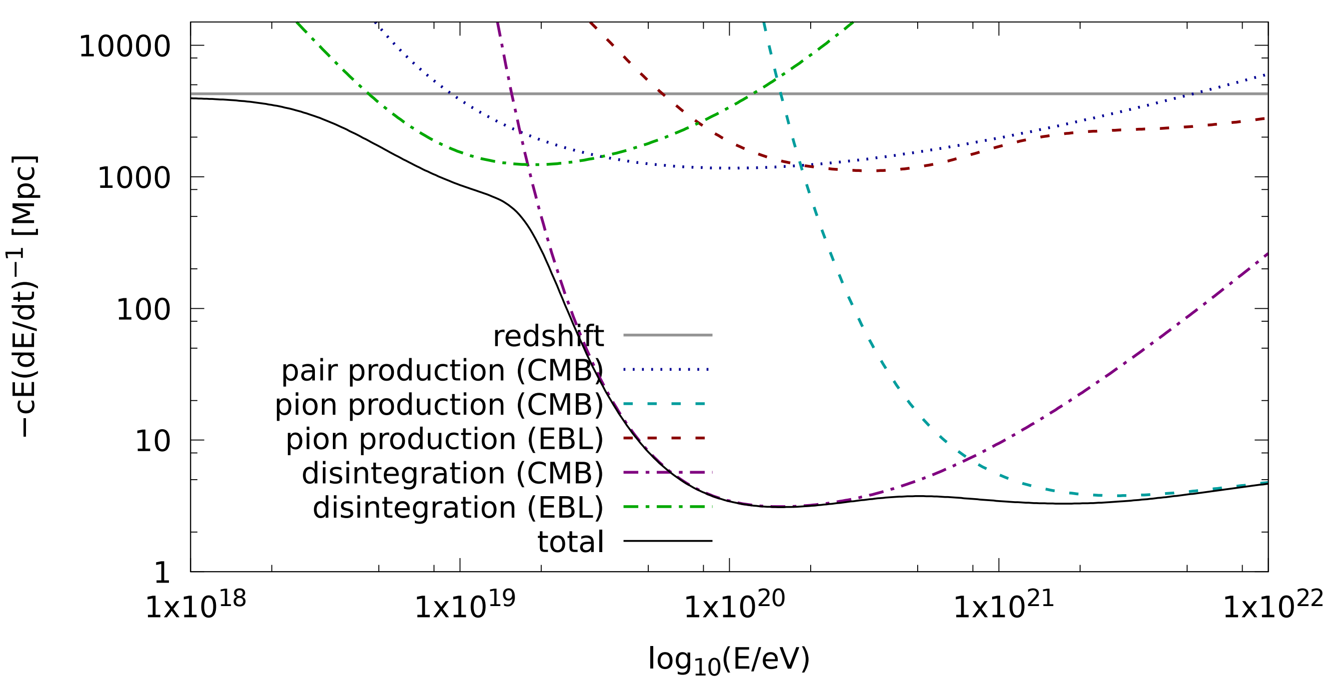
(hadronic processes preferred)

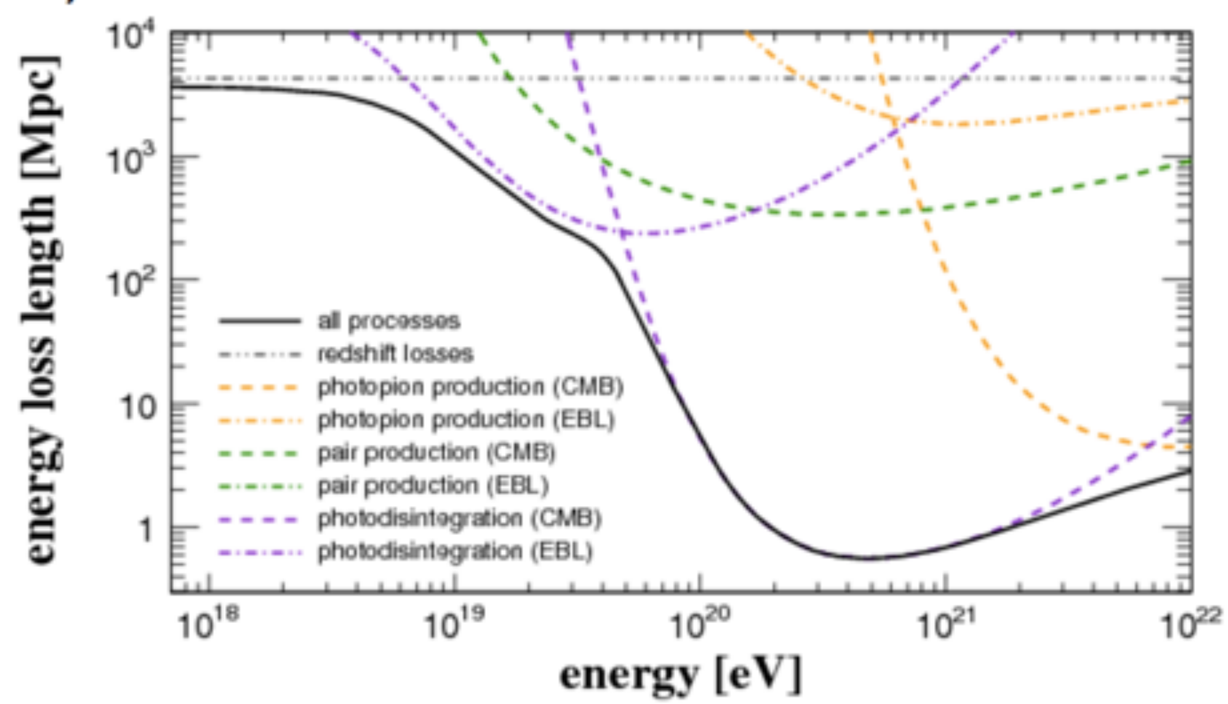
Hypothesis : CR flux ∝ non-thermal flux of photons

➡ Calorimetric argument: natural for environments such that starburst galaxies

Composition and horizons at UHE



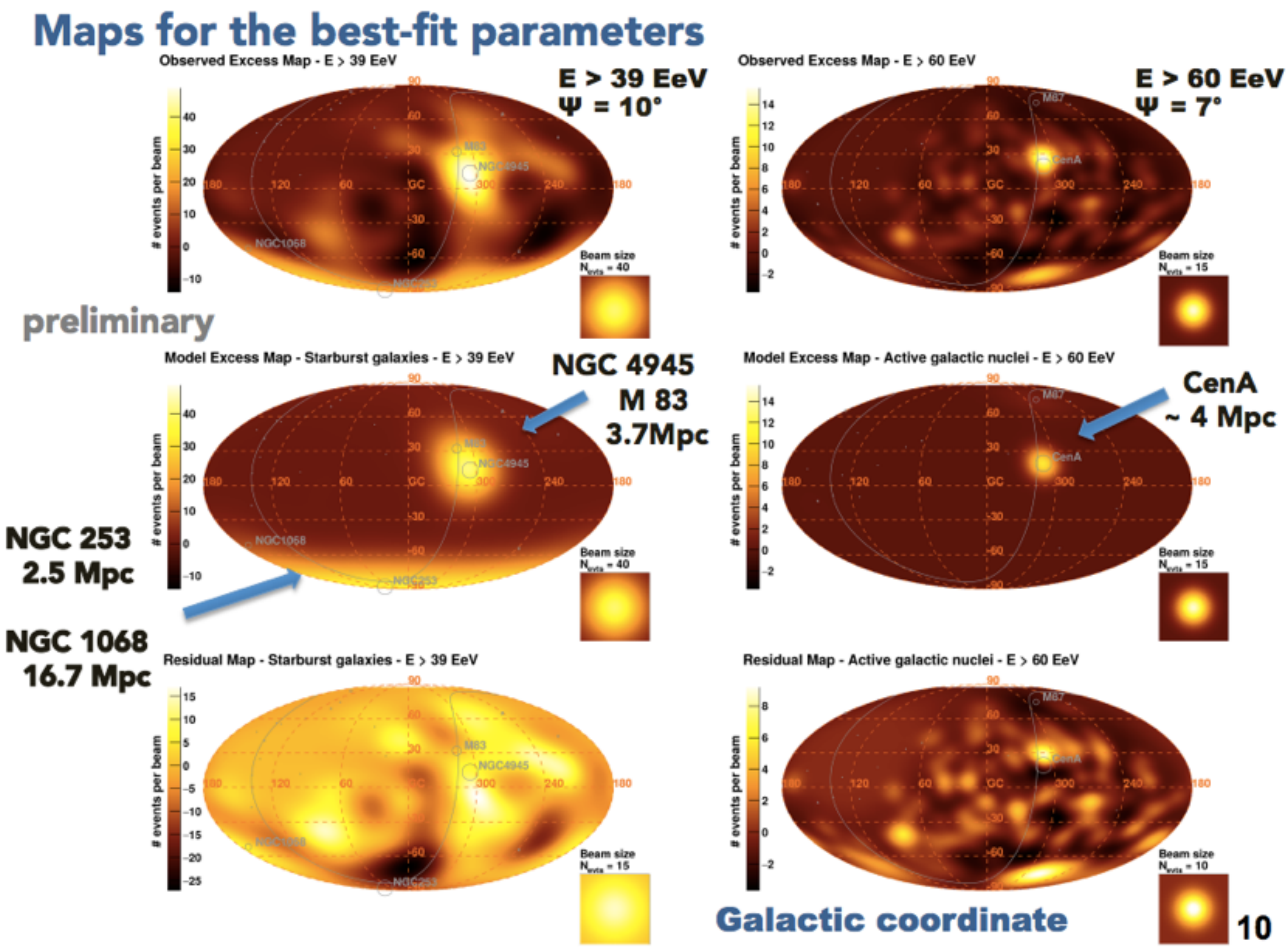




[Alves Batista, Boncioli, Di Matteo et al., JCAP10(2015)063]

☞ Limited horizons @ 30-40 EeV

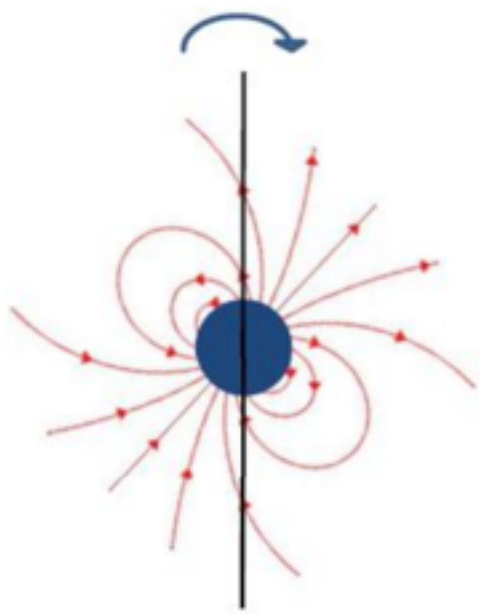
Sky maps

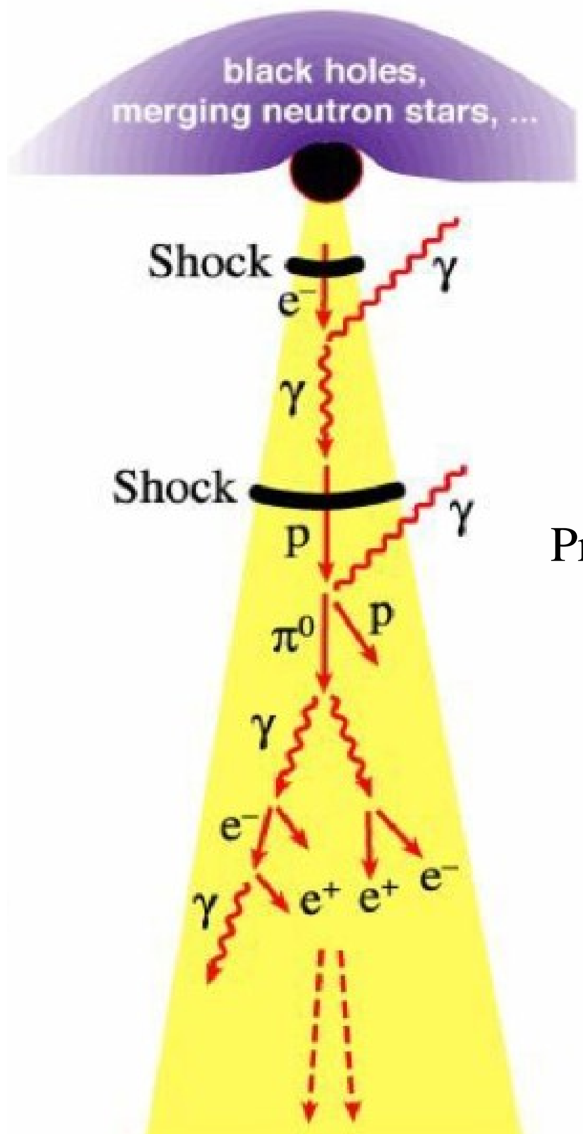

Maps for the best-fit parameters
Observed Excess Map - E > 39 EeV
E > 39 EeV
Ψ = 10°
Observed Excess Map - E > 60 EeV
E > 60 EeV
Ψ = 7°
preliminary
Model Excess Map - Starburst galaxies - E > 39 EeV
NGC 4945
M 83
3.7Mpc
Model Excess Map - Active galactic nuclei - E > 60 EeV
CenA
~ 4 Mpc
NGC 253
2.5 Mpc
NGC 1068
16.7 Mpc
Residual Map - Starburst galaxies - E > 39 EeV
Residual Map - Active galactic nuclei - E > 60 EeV
events per beam
Beam size
Galactic coordinate
10

Cosmic accelerators?

rotating **B**

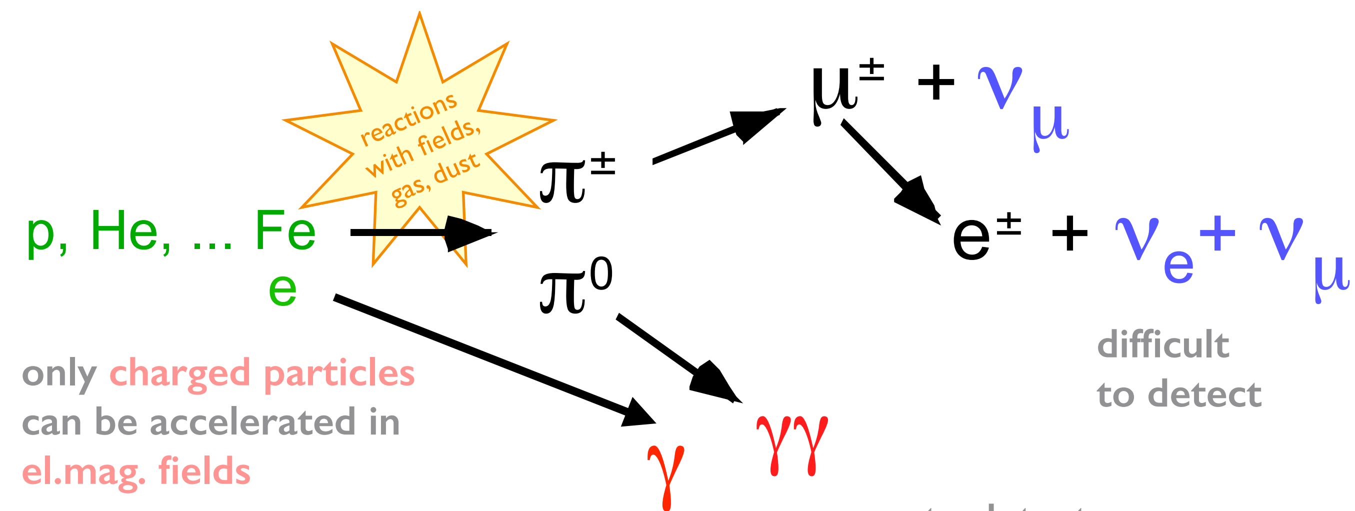
turbulent **B**





P1

multi-messenger cascade



only charged particles
can be accelerated in
el.mag. fields

easy to detect

“multi-messenger astrophysics”

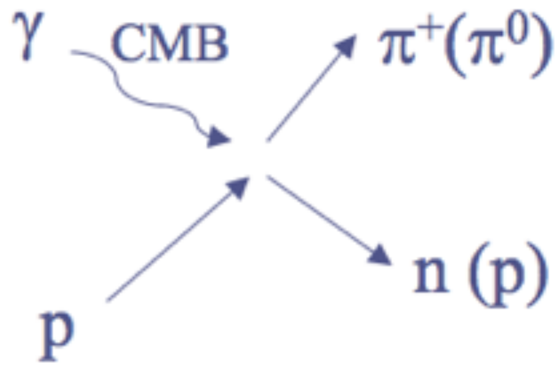
but gamma rays are currently
the most “productive” messengers.

γ,ν
point back to sources
(good for astronomy)
but serious backgrounds

$\langle E \rangle$ $\langle E^2 \rangle$

Constraints from the Auger Observatory?

GZK cutoff

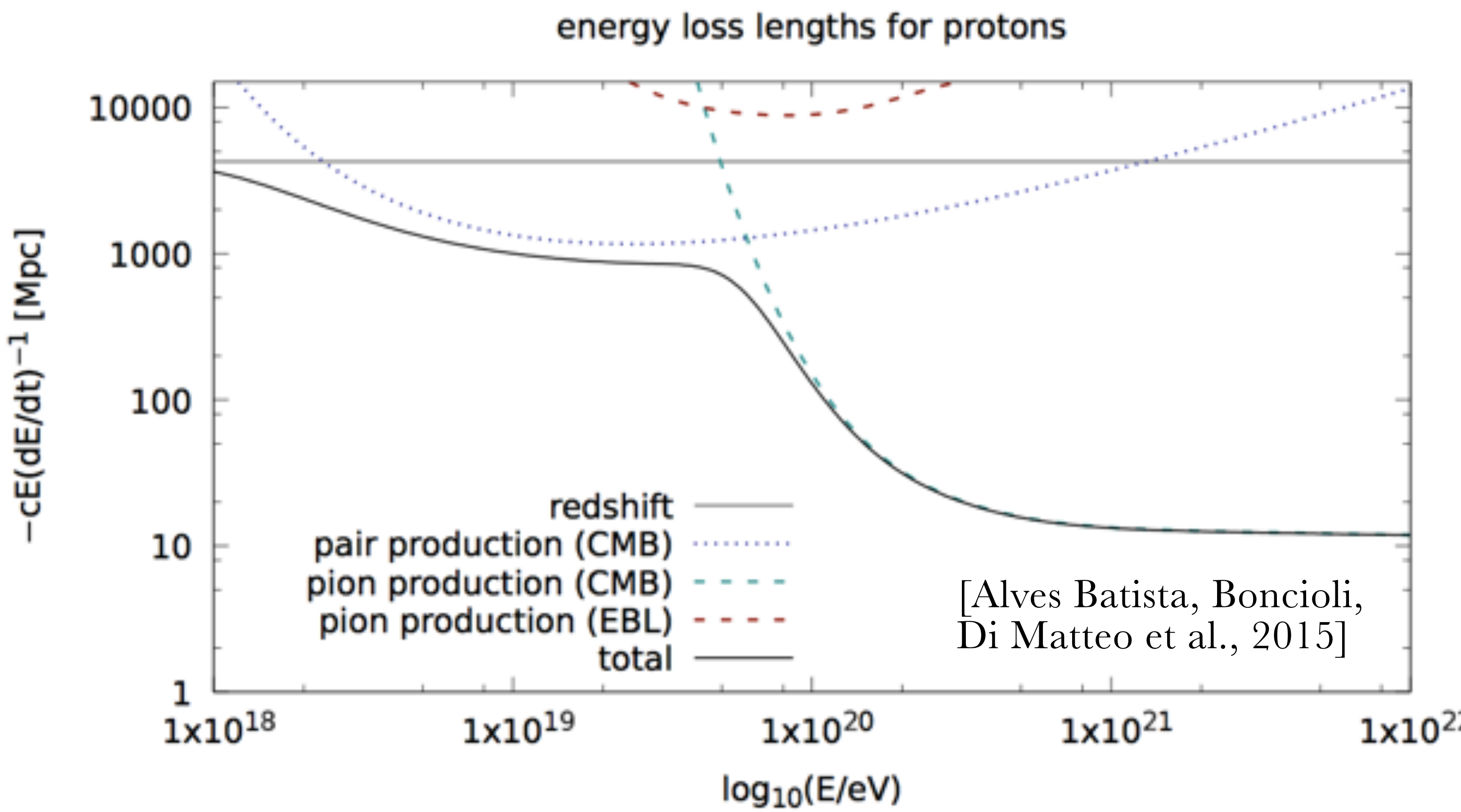


Example with protons

$$\varepsilon_\gamma > \frac{m_\pi m_p}{\varepsilon_p} \sim 10^{-3} \varepsilon_{20}^{-1} \text{ eV} \Rightarrow \quad n_\gamma \sim \frac{400}{\text{cm}^3} \exp\left[1 - \frac{3}{\varepsilon_{20}}\right]$$

$$\lambda_E \sim \frac{m_p}{m_\pi} \frac{1}{n_\gamma \sigma_{\gamma p}}$$

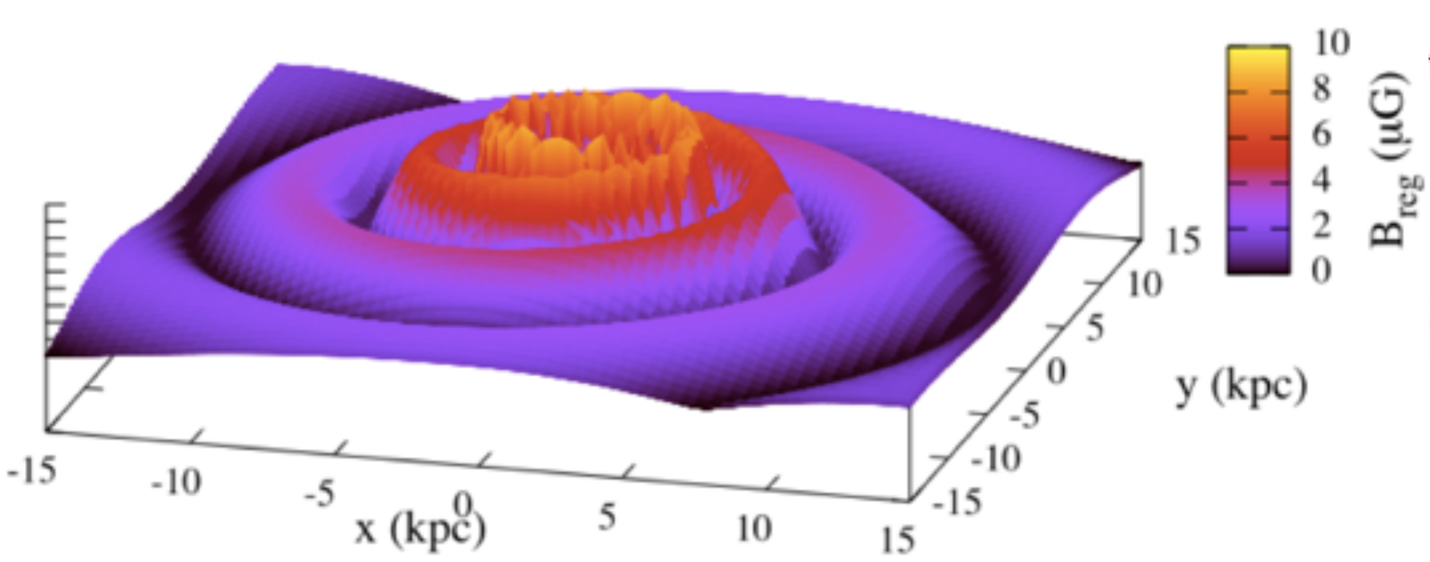
$$\sim 11 \exp\left[\frac{3}{\varepsilon_{20}} - 1\right] \quad \text{Mpc}$$



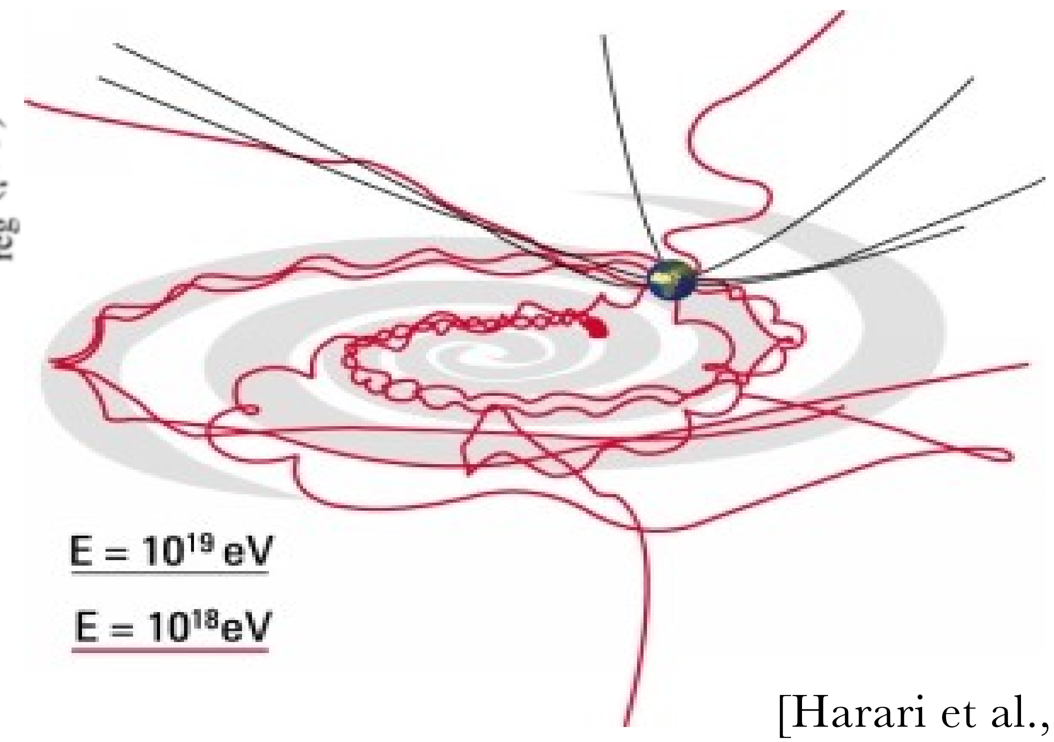
Almost same conclusions for nuclei (photo-disintegration)

➡ Reduction of the CR horizon at UHE

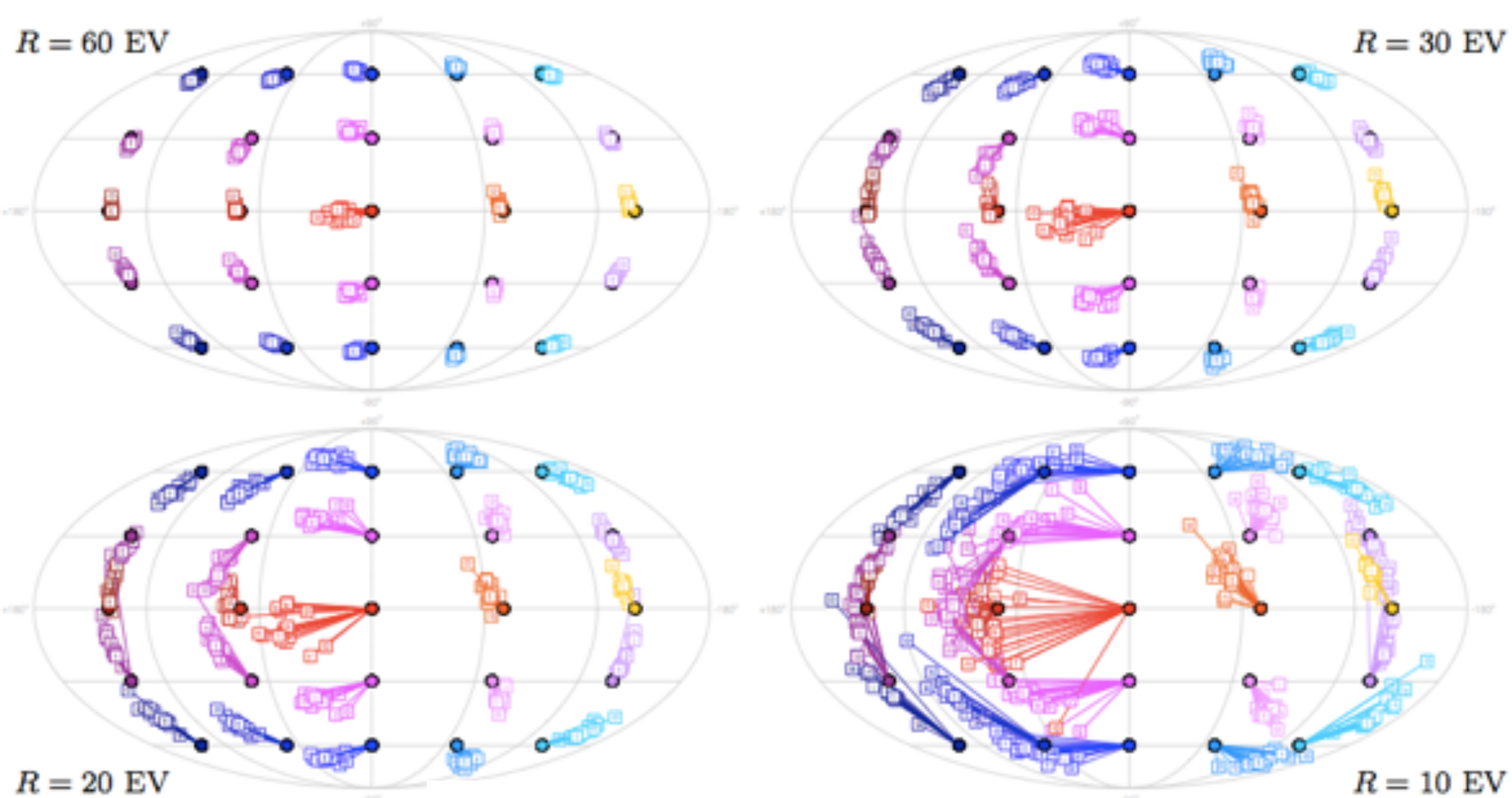
Magnetic deflections



[Jansson & Farrar 2012]



[Harari et al., 1999]



[Unger & Farrar 2017]

At UHE, CRs may be rigid enough to point back to their sources within a few degrees

+ Reduced horizon

➡ Possibility to identify nearby sources?