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

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O. Deligny (CNRS/IN2P3 - IJCLab Orsay), for the Pierre Auger Collaboration

i) UHECRs and the Pierre Auger Observatory

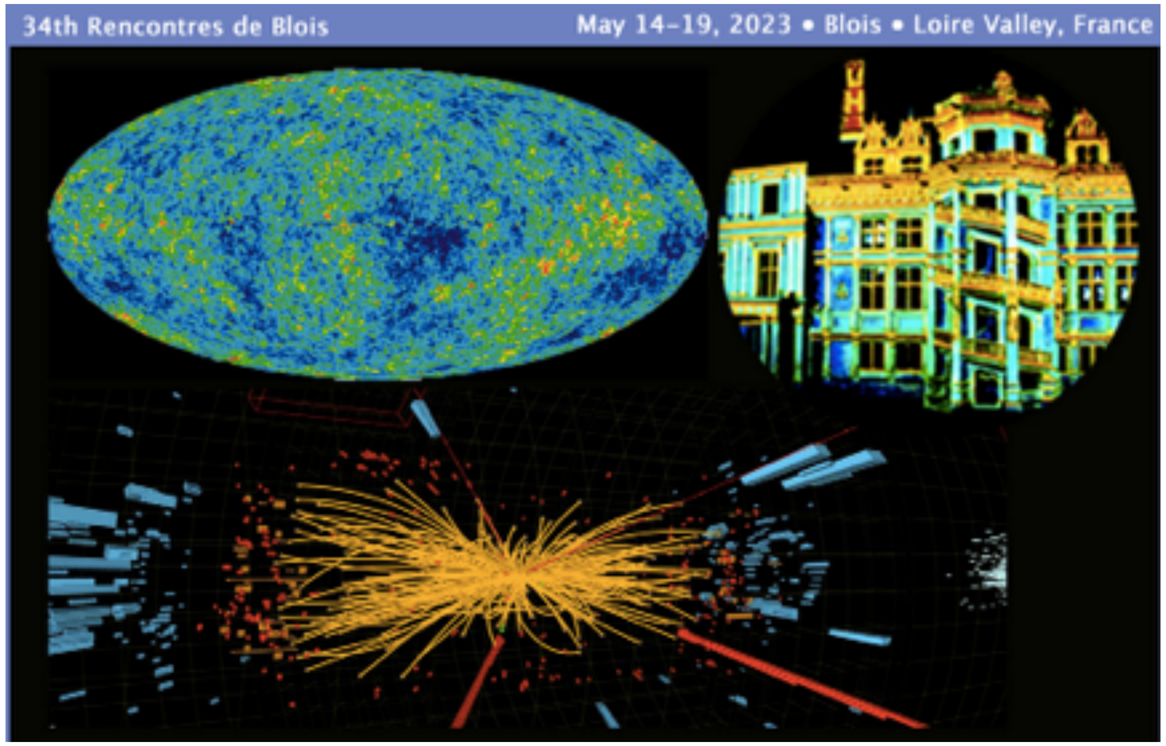
ii) Searching for sources in arrival directions

iii) Energy spectrum and mass composition: probing source properties

iv) Astrophysical interpretations

v) Photons, neutrinos, multi-messenger, BSM, (super-heavy) dark matter

vi) Puzzles in extensive air showers



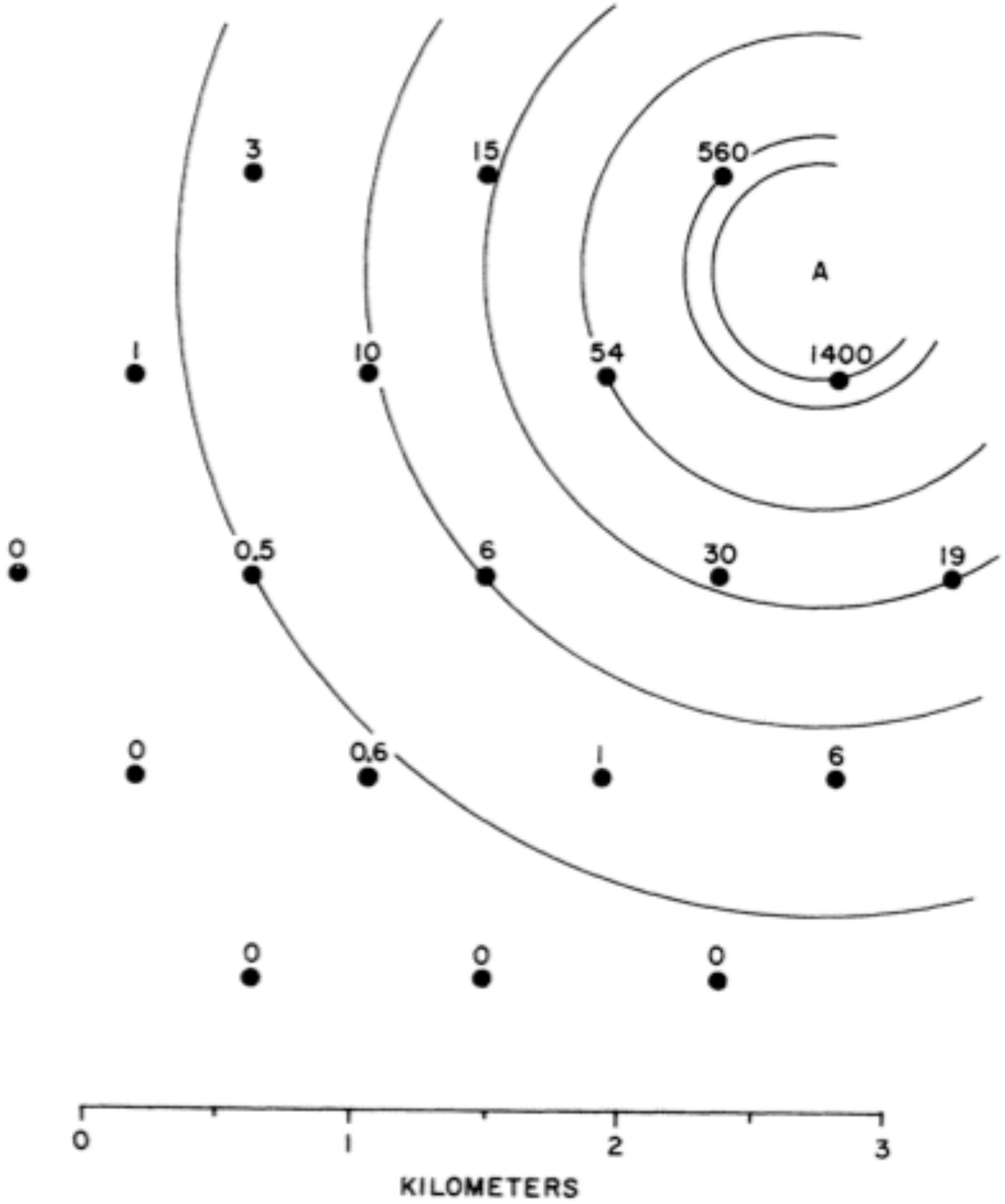
34th Rencontres de Blois

May 14–19, 2023 • Blois • Loire Valley, France

i) Ultra-High Energy Cosmic Rays and The Pierre Auger Observatory

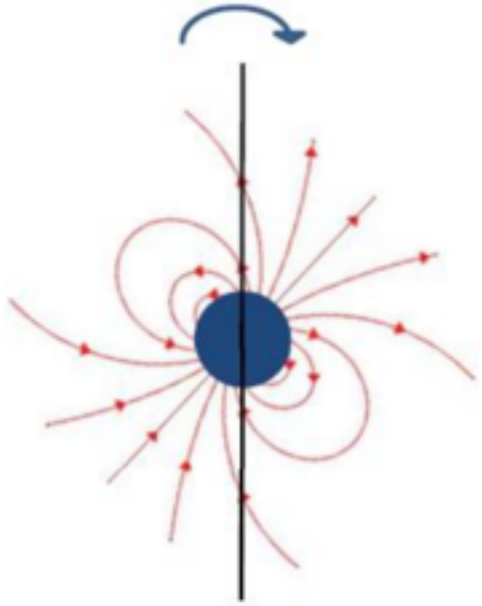
UHECRs: ~10^{20} eV!

[Linsley, PRL 10:146–148]



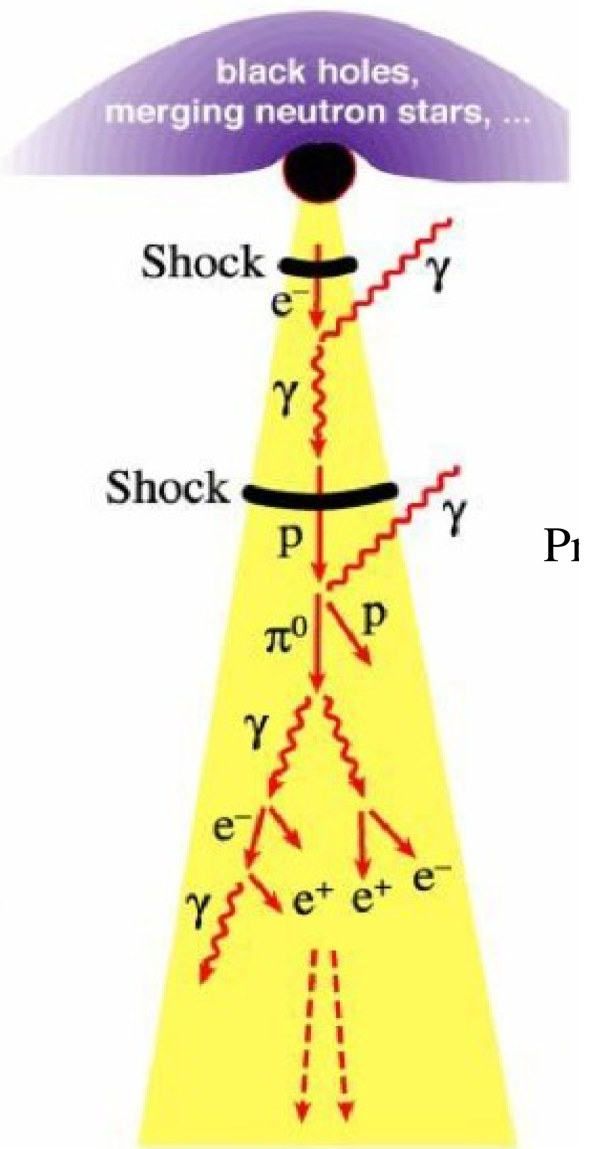
Cosmic accelerators?

« Rotating **B** »
E.B ≠ 0



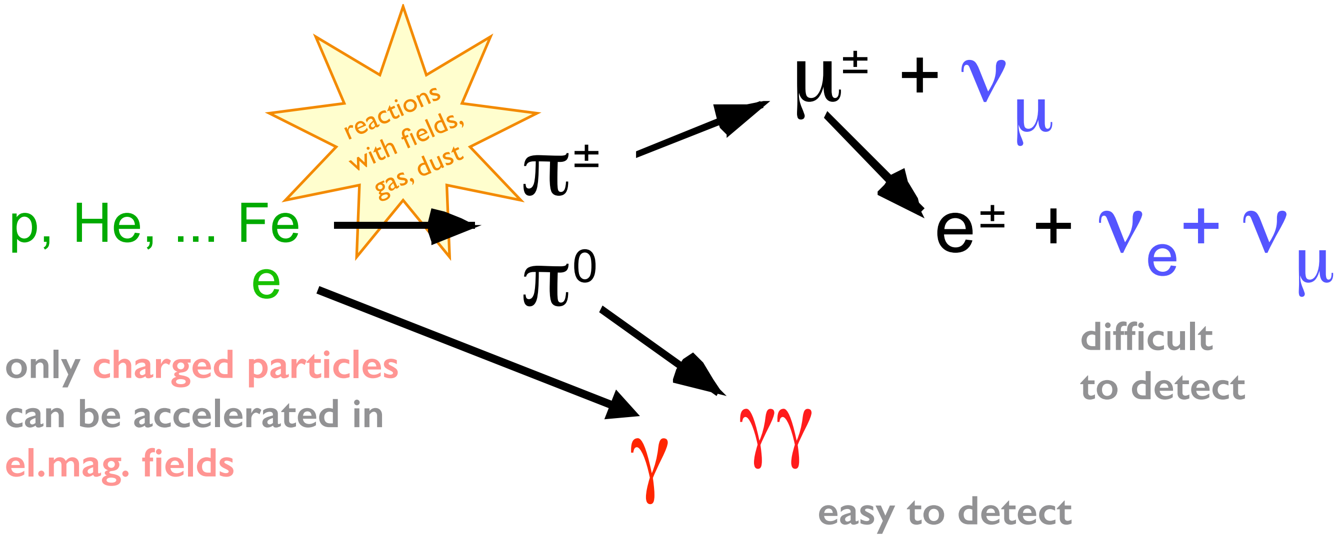
$E^2-B^2>0$

« Turbulent **B** »
E.B = 0



$E^2-B^2<0$

multi-messenger cascade



reactions with fields, gas, dust

p, He, ... Fe
e

$\pi^\pm$ → $\mu^\pm + \nu_\mu$ → $e^\pm + \nu_e + \nu_\mu$

π^0 → $\gamma\gamma$

γ

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

difficult to detect

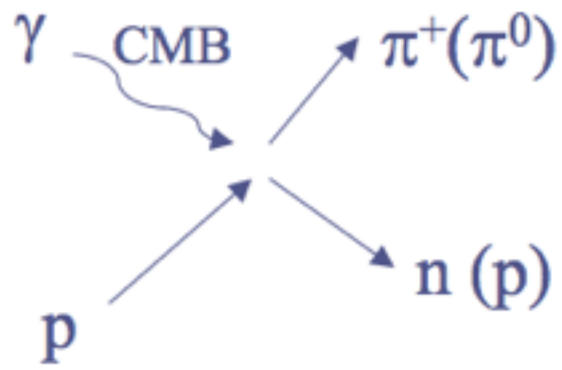
easy to detect

"multi-messenger astrophysics"

but gamma rays are currently the most "productive" messengers.

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

GZK cutoff

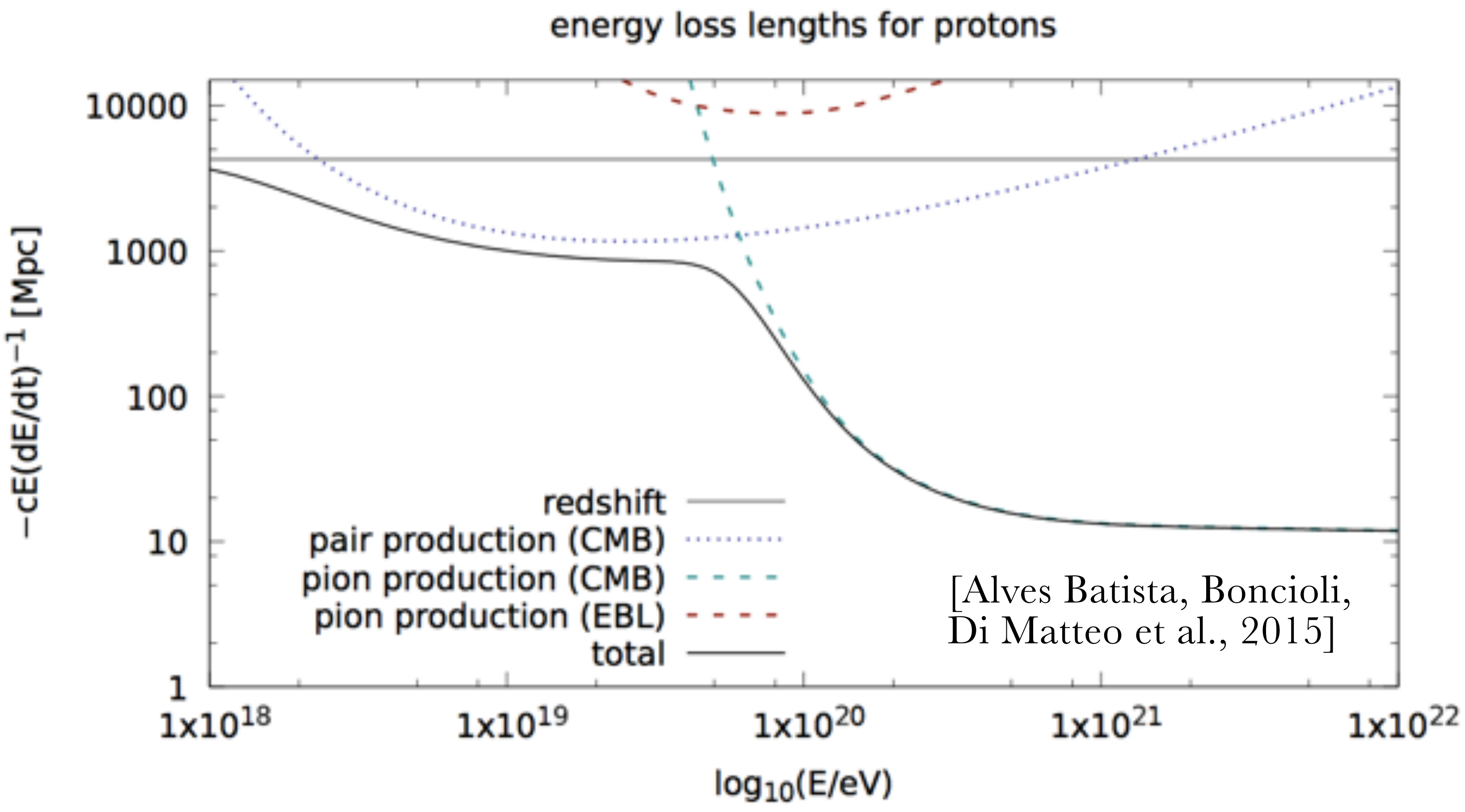


Example with protons

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

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

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

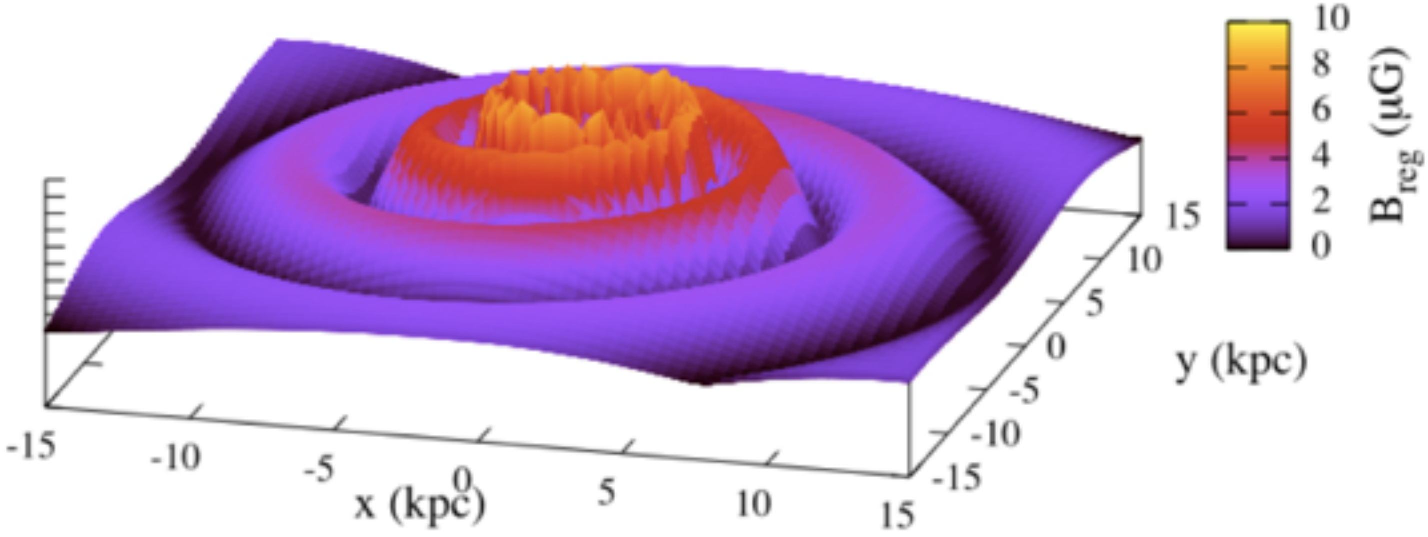


[Alves Batista, Boncioli, Di Matteo et al., 2015]

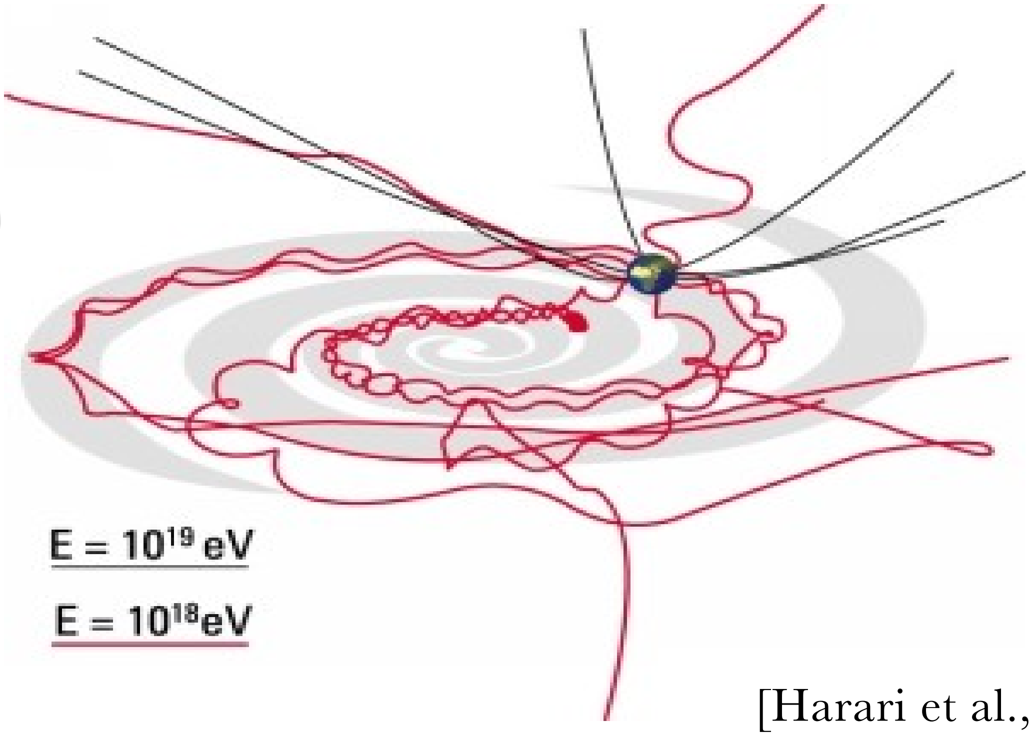
Almost same conclusions for nuclei (photo-disintegration)

➡ Reduction of the CR horizon at UHE

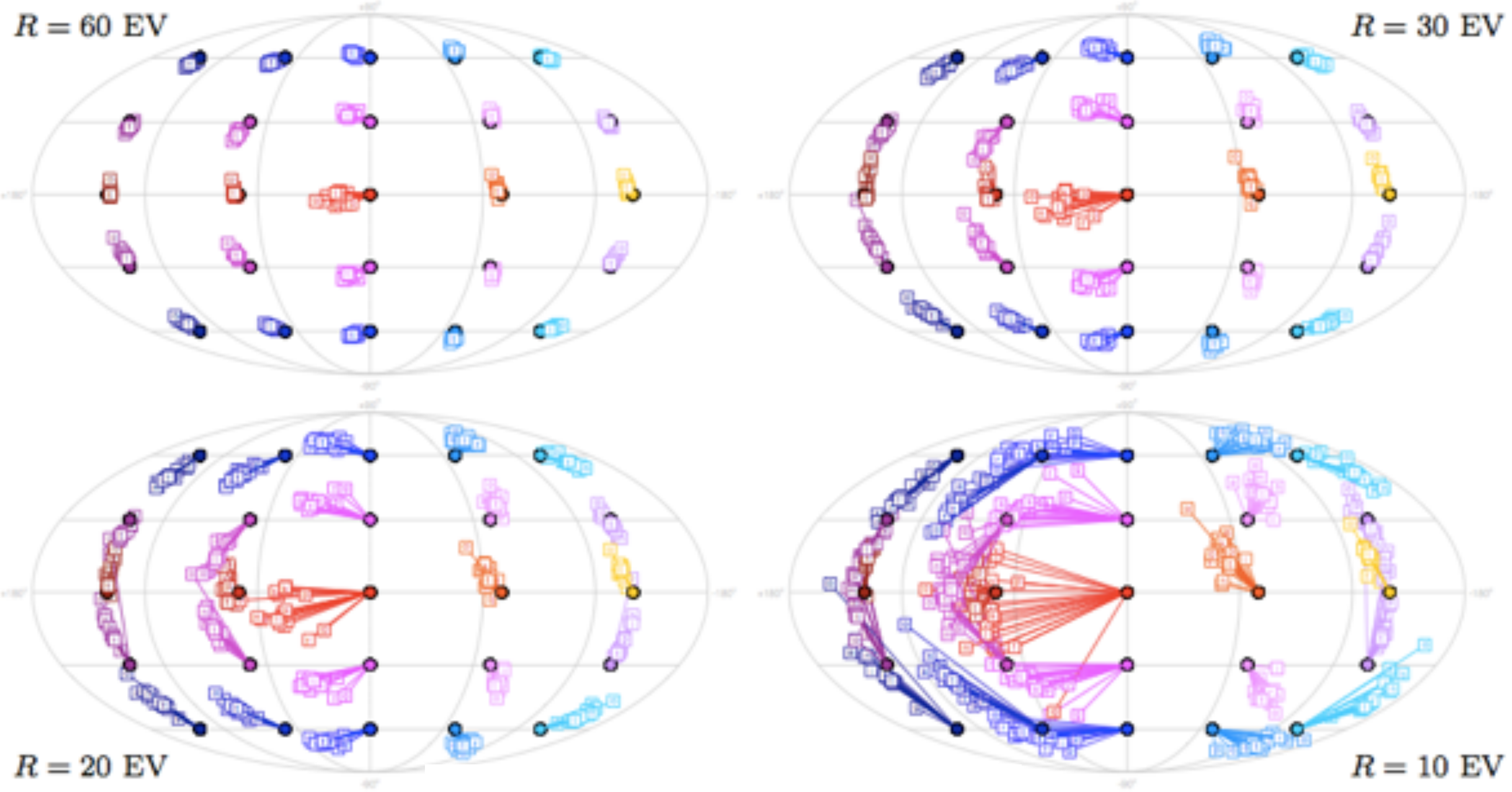
Magnetic deflections — GMF contribution



[Jansson & Farrar 2012]



[Harari et al., 1999]



[Unger & Farrar 2017]

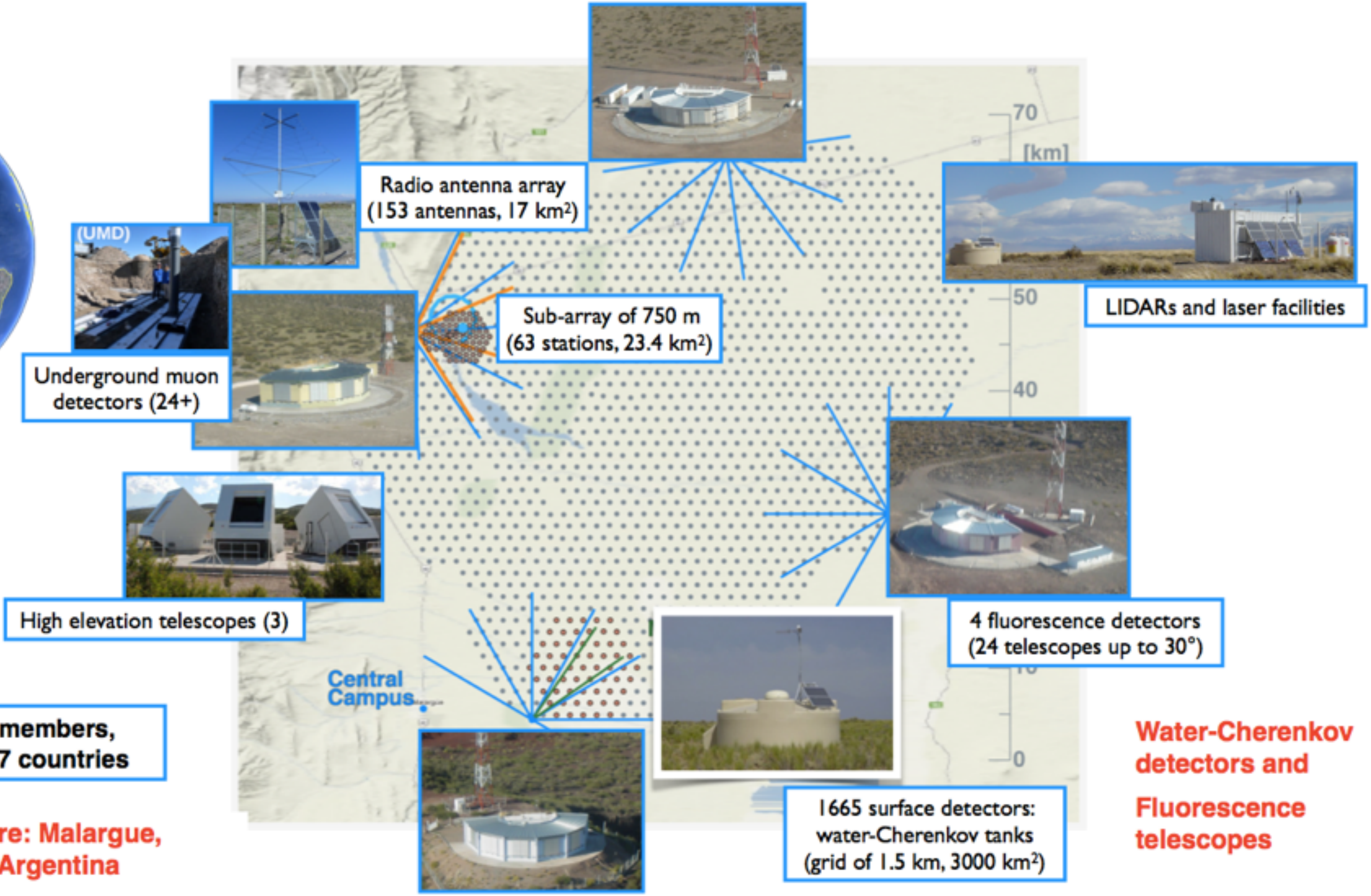
At UHE, CRs may be rigid enough to point back to their sources within a few degrees

\+ Reduced horizon

➡ Possibility to identify nearby sources?

The Pierre Auger Cosmic Ray Observatory

Pierre Auger Observatory
Province Mendoza, Argentina



Radio antenna array
(153 antennas, 17 km²)

Sub-array of 750 m
(63 stations, 23.4 km²)

LIDARs and laser facilities

Underground muon
detectors (24+)

High elevation telescopes (3)

4 fluorescence detectors
(24 telescopes up to 30°)

1665 surface detectors:
water-Cherenkov tanks
(grid of 1.5 km, 3000 km²)

More than 400 members,
98 institutes, 17 countries

Southern hemisphere: Malargue,
Province Mendoza, Argentina

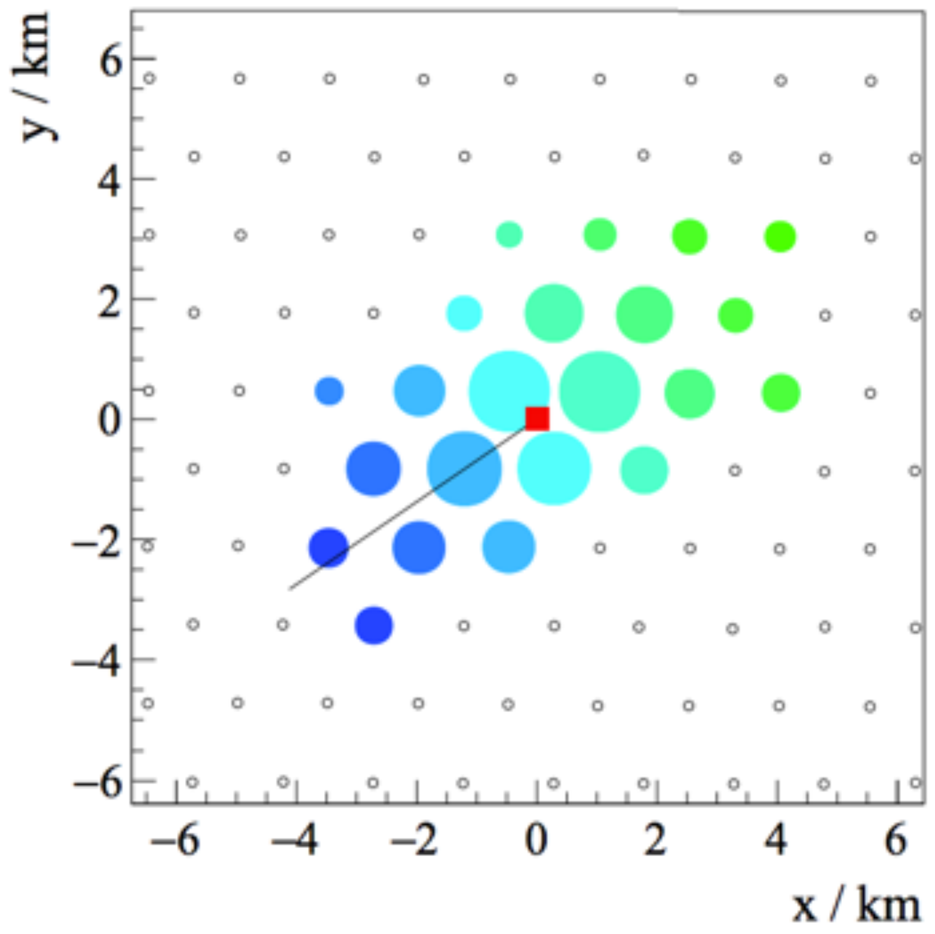
Water-Cherenkov
detectors and

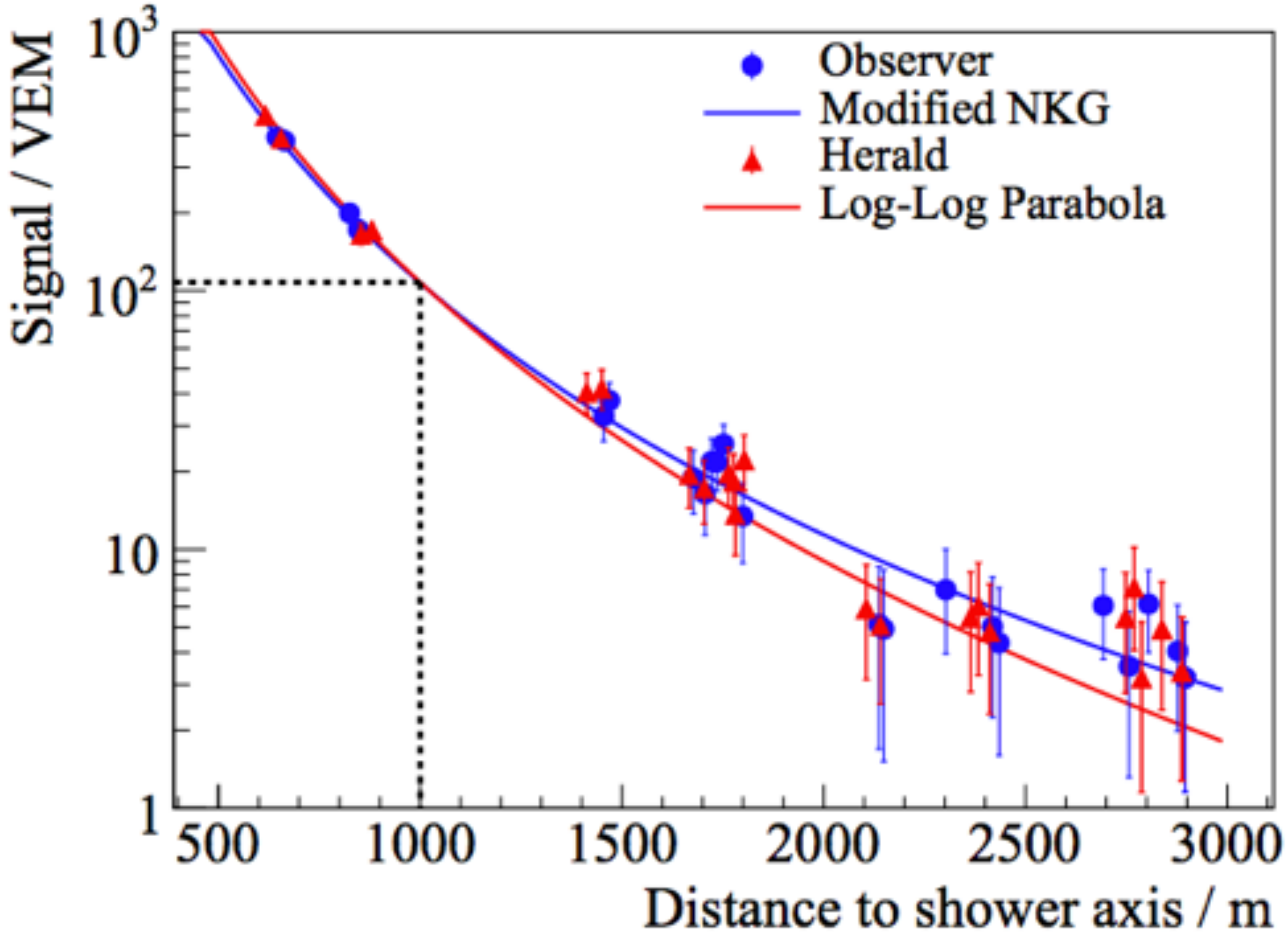
Fluorescence
telescopes

[NIM 798:172–213, 2015]

Surface Detectors

Track-length integral → Air-shower size

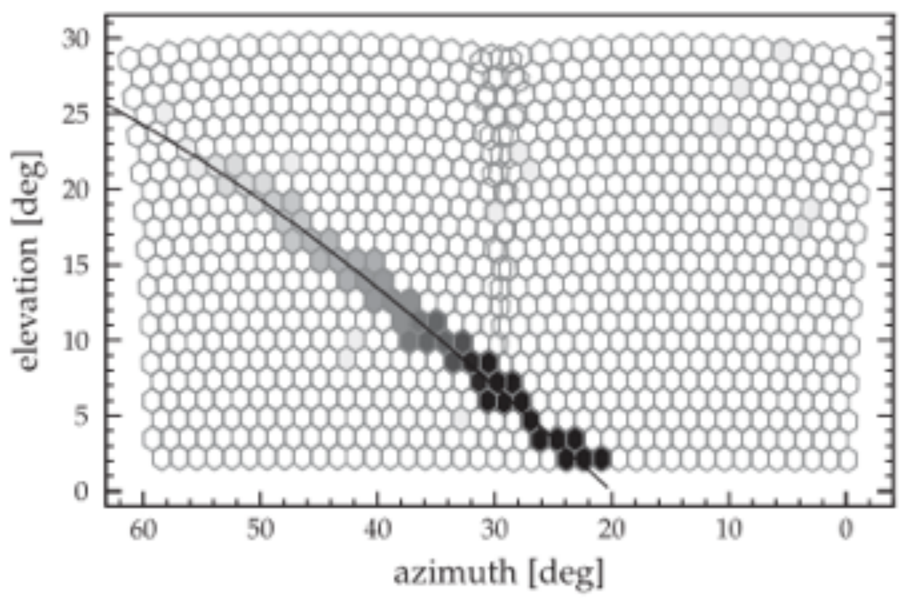




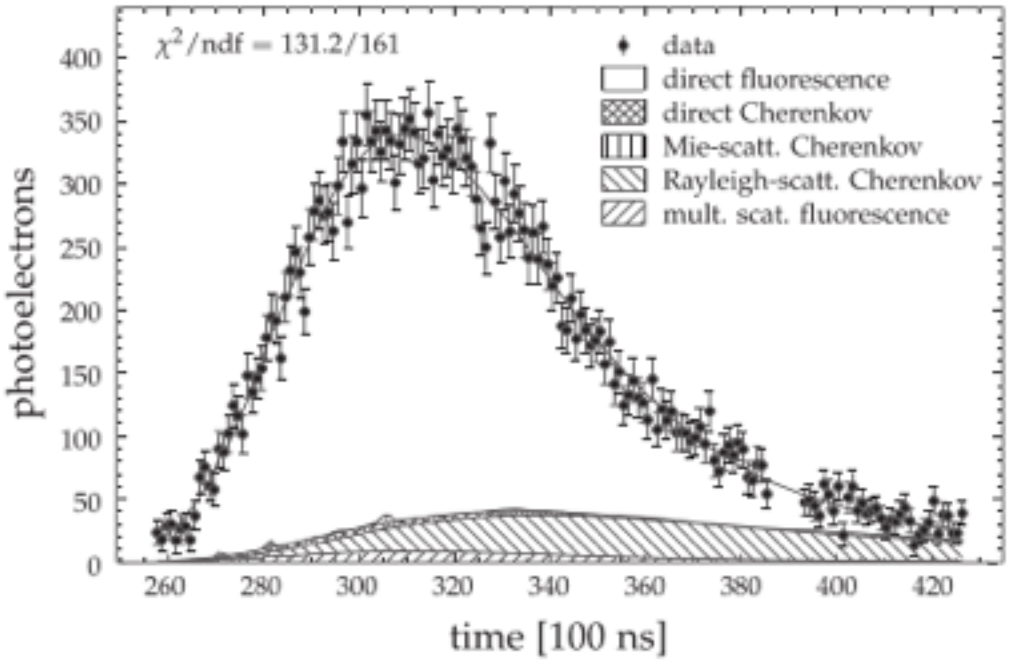
$S(r_{\mathrm{opt}})$ as shower-size estimate **[Hillas, Acta Phys. Acad. Sci. Hung., 29, Suppl. 3, page 355]**

[JINST 15 (2020) P10021]

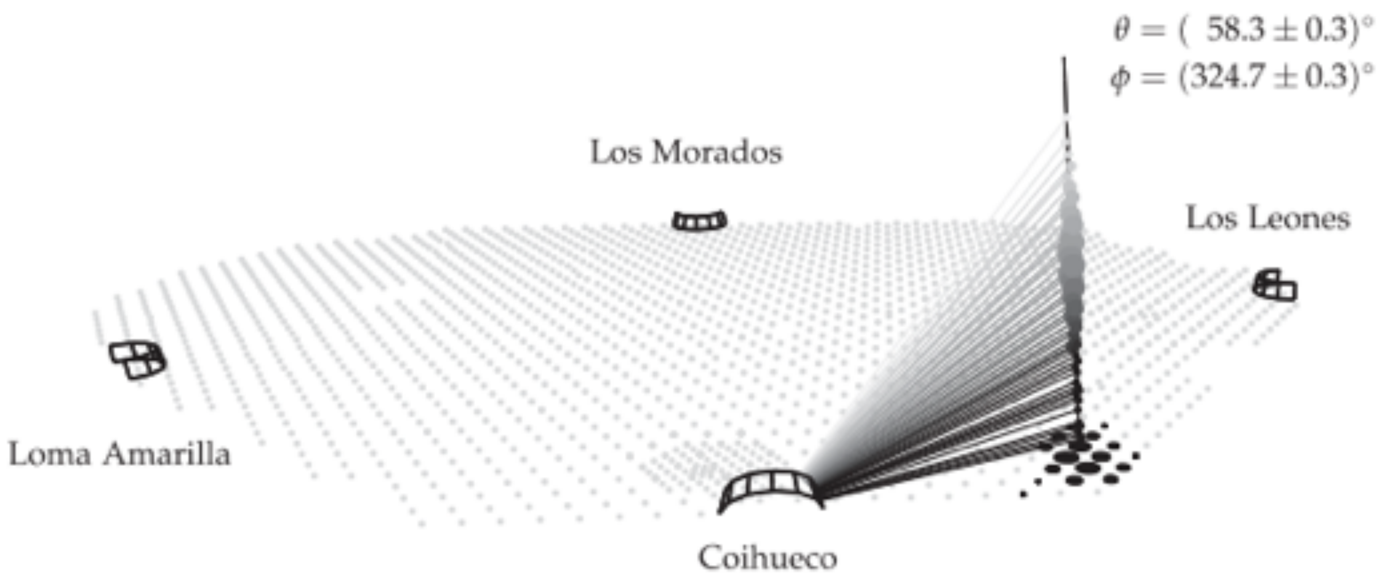
Longitudinal profile reconstruction



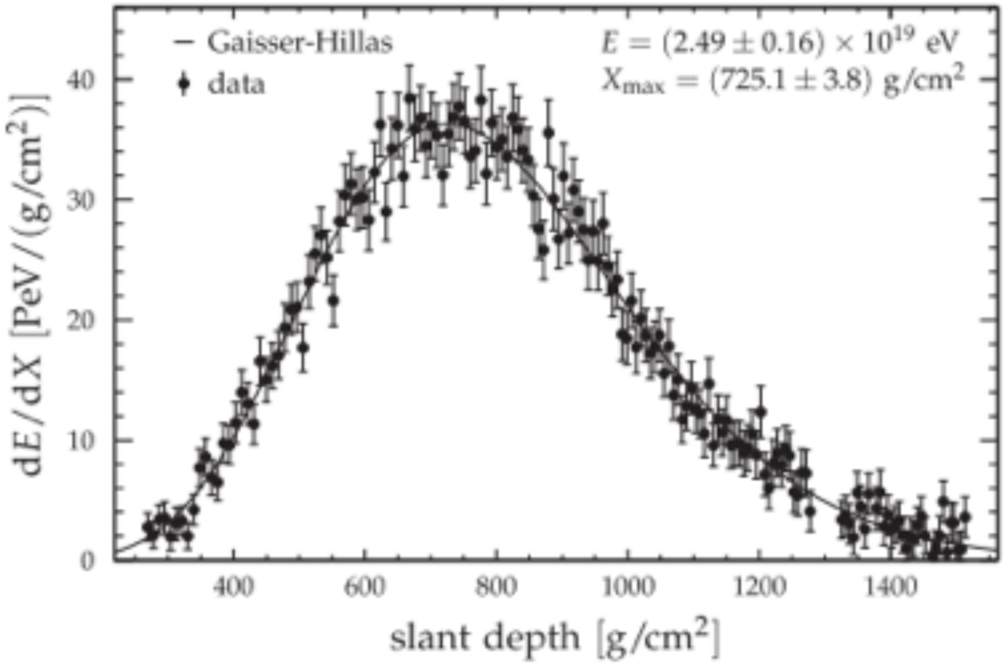
(a) Camera view. The timing of the pixel pulses is denoted by shades of gray (early = light, late = dark). The line shows the shower detector plane.



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

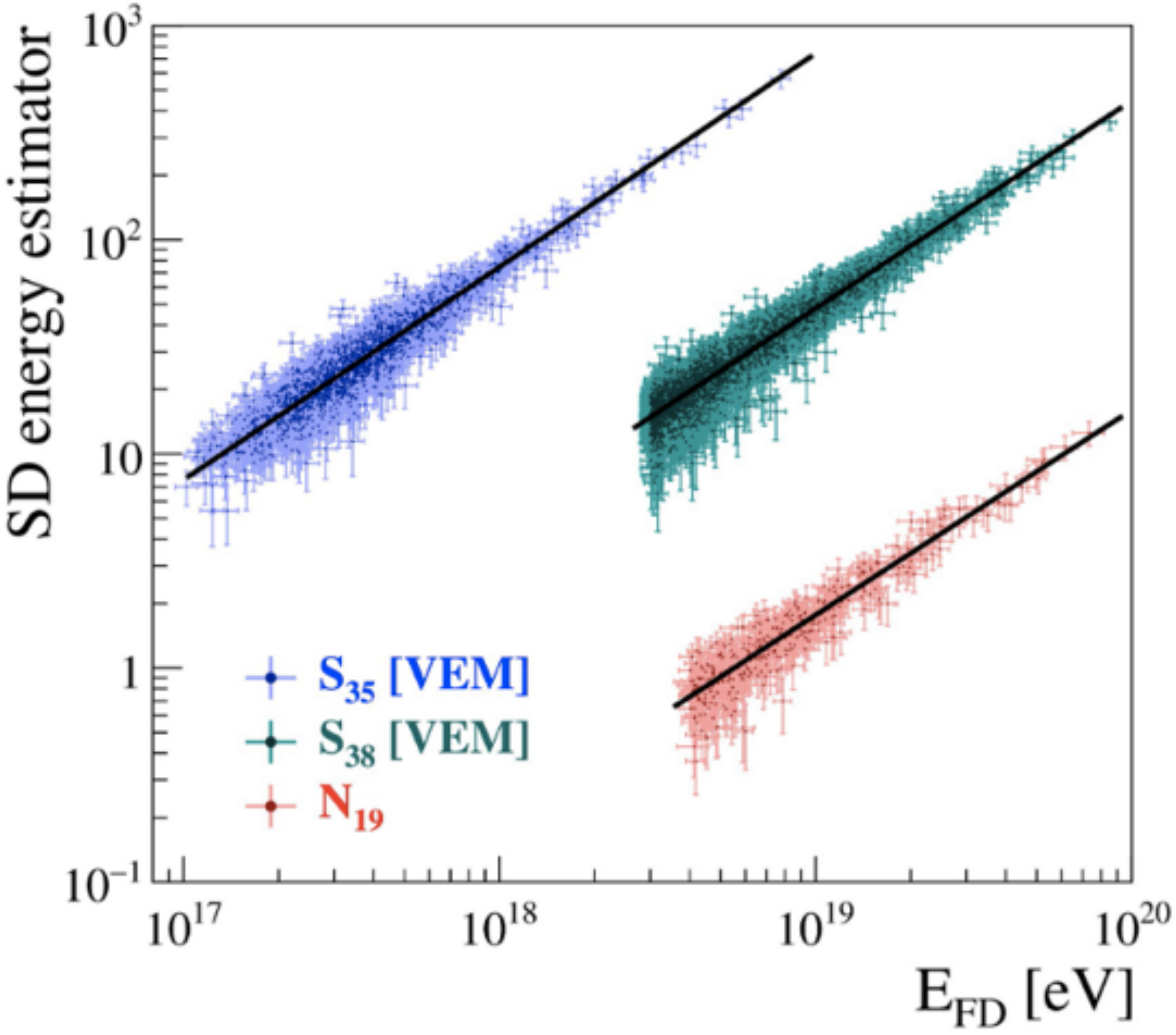


(b) Event geometry. Pixel viewing angles are shown as shaded lines and the shower light and surface detector signals are illustrated by markers of different size in logarithmic scale.



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

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

ii) Searching for sources in arrival directions

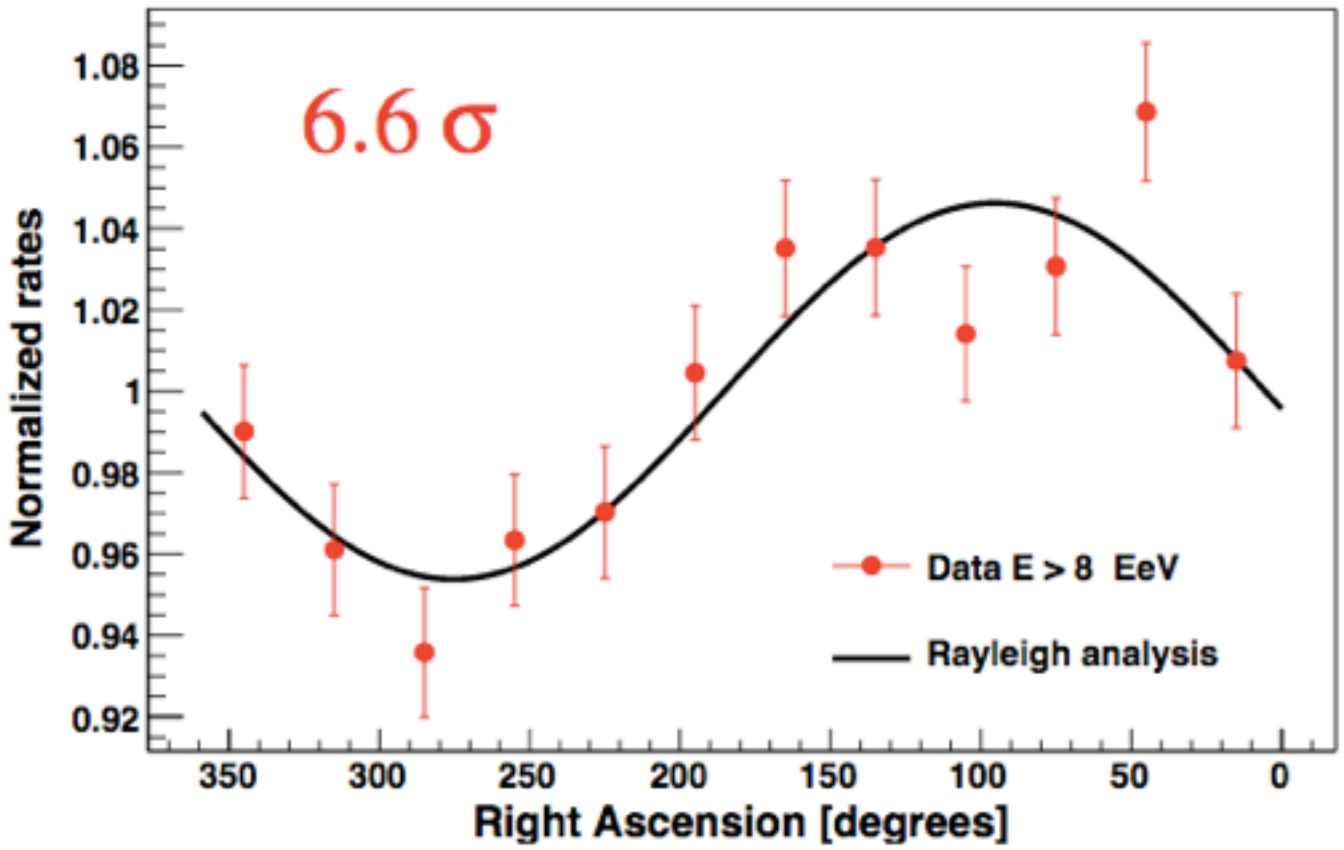
➡ Aiming to capture in the UHECR arrival directions a pattern suggestive in an evident way of a class of astrophysical objects.

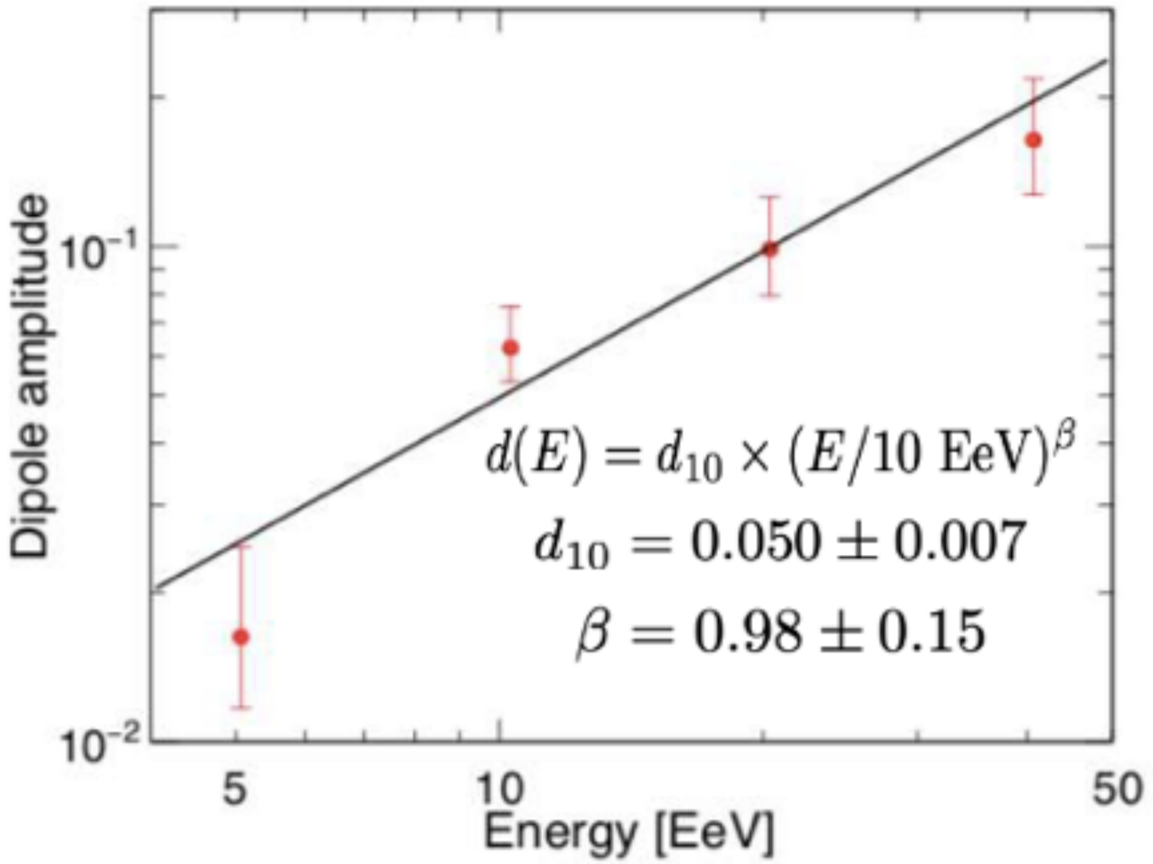
First harmonic in RA

- 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

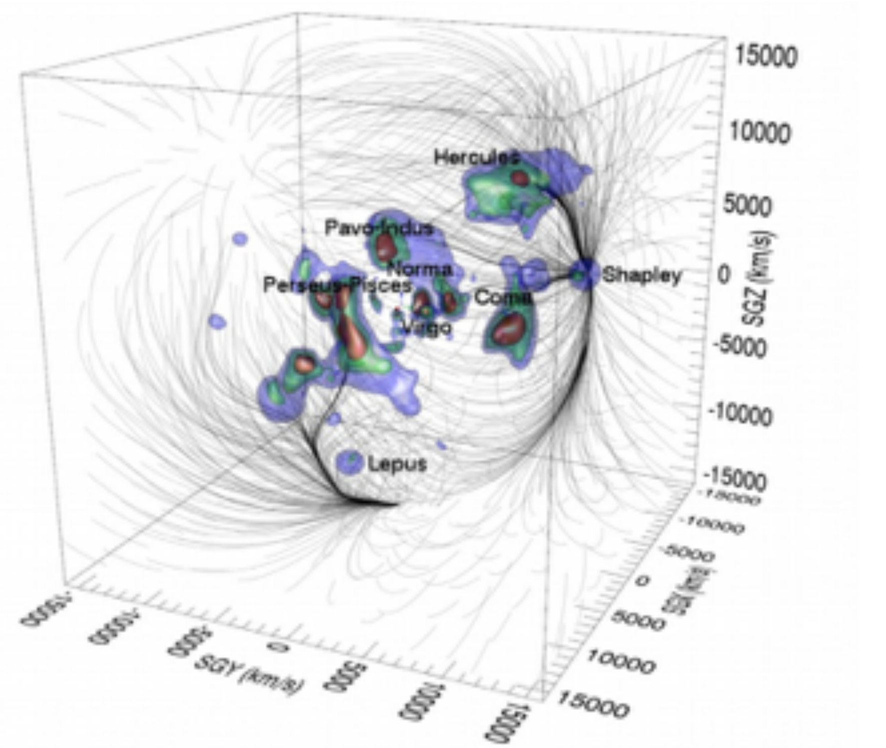
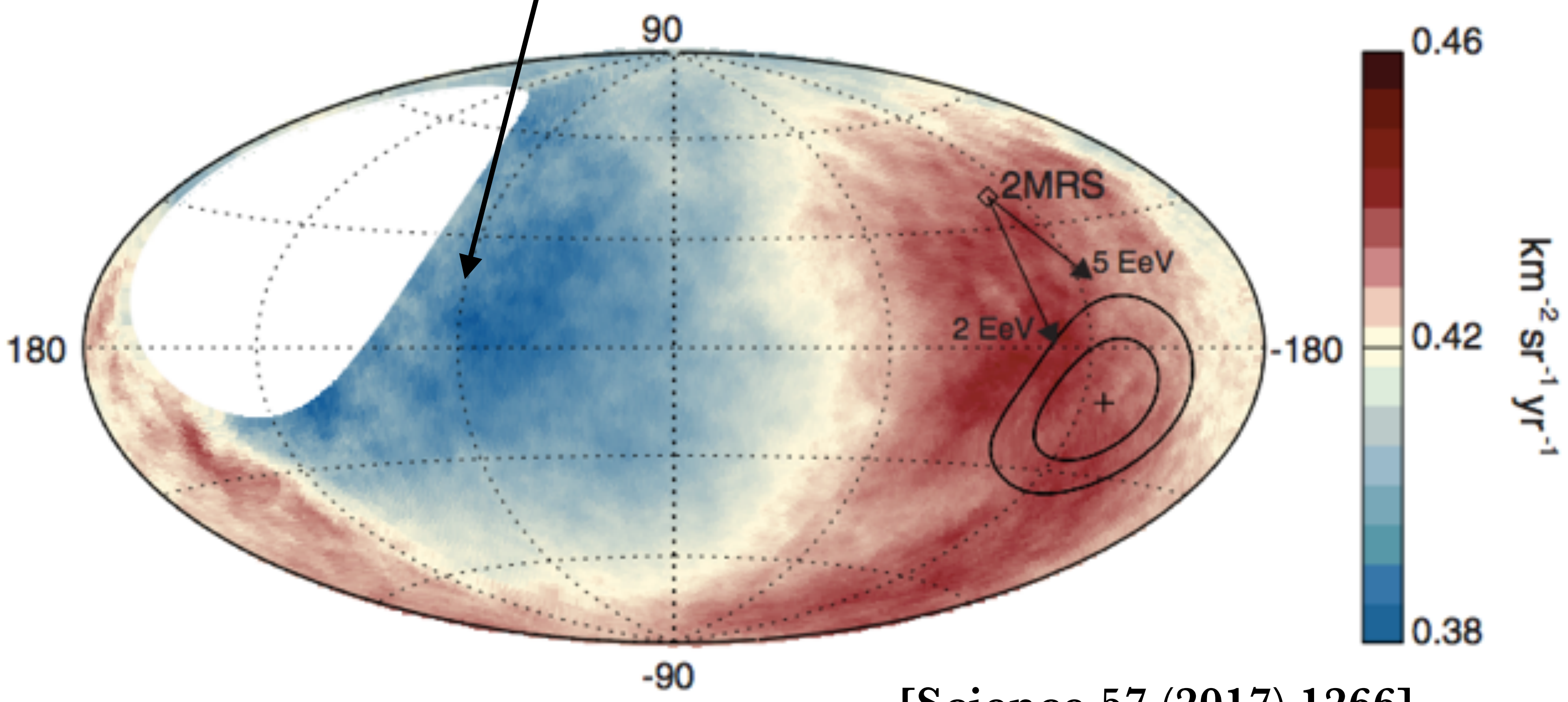


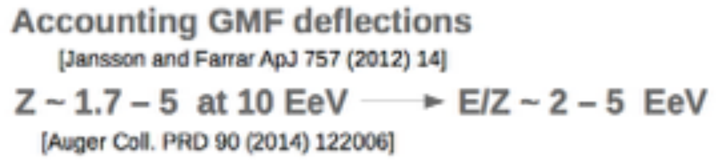
Fig. ED 1. — Structure within a cube extending 16,000 km s^{-1} (~200 Mpc)

Tully, Courtois, Hoffman, Pomarède, Nature 2014

Direction of the local void



[Science 57 (2017) 1266]



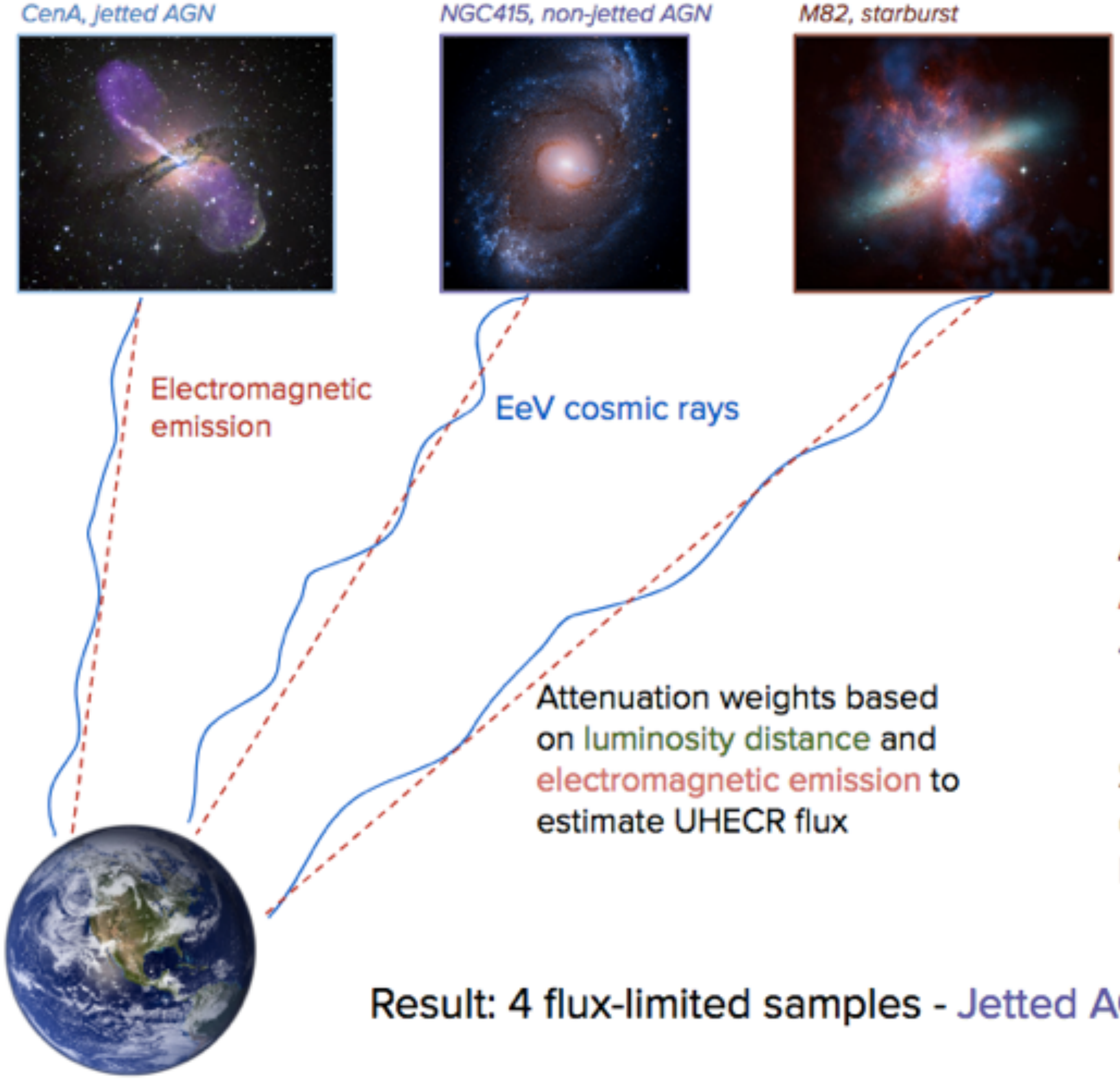
Accounting GMF deflections

[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]

Catalog-based correlations

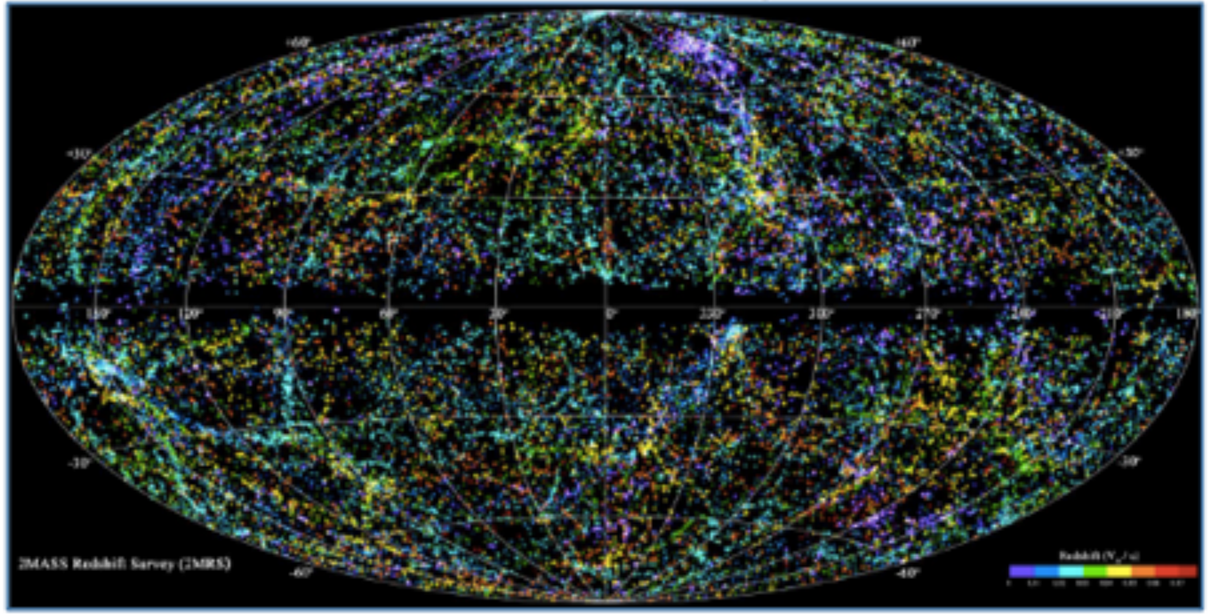


Electromagnetic emission

EeV cosmic rays

Attenuation weights based on luminosity distance and electromagnetic emission to estimate UHECR flux

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

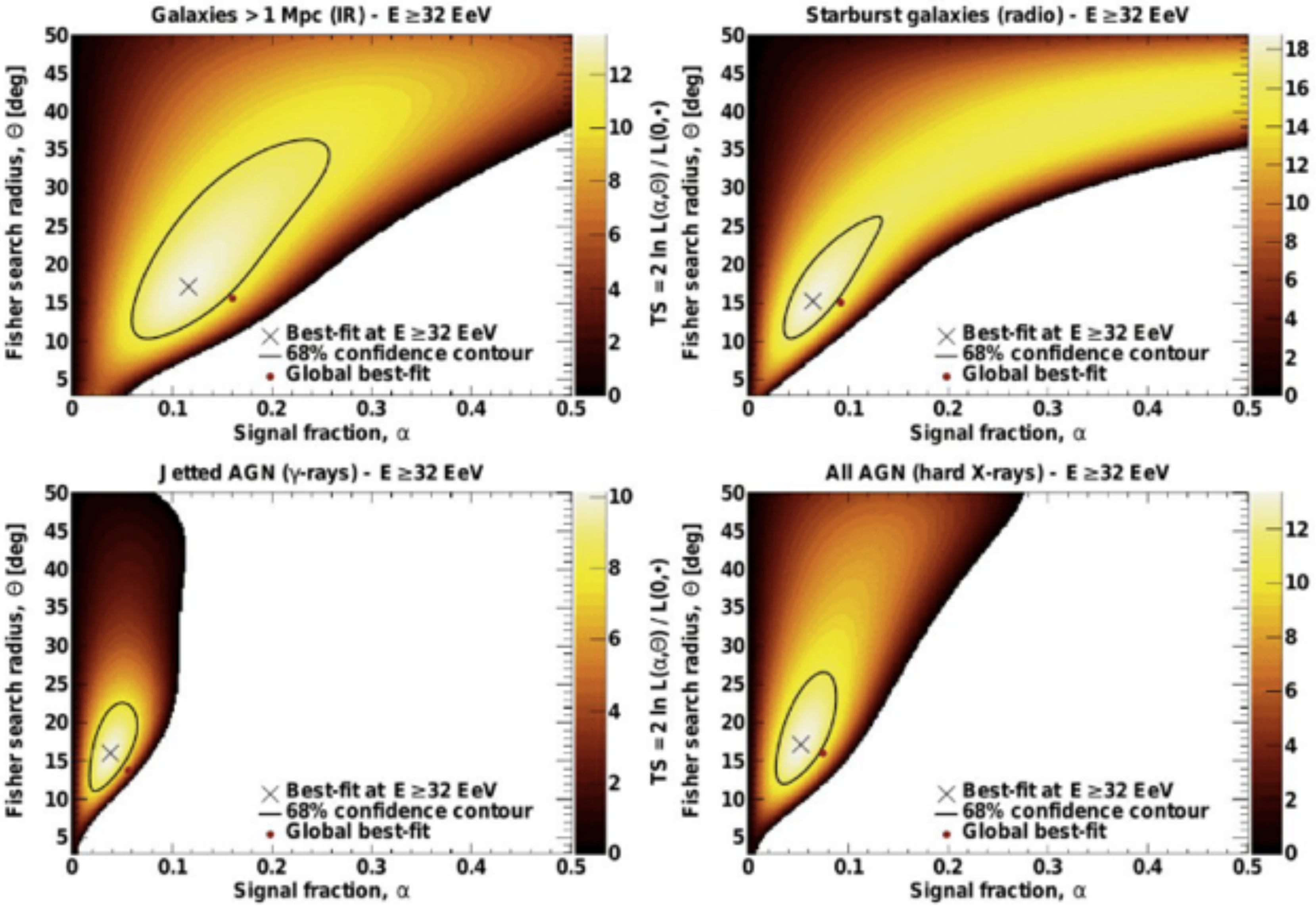
Generic/**stellar mass = IR** from 2MRS (>40’000 galaxies 2.2 μm)

Burst = radio from Lunardini+19 (44 galaxies, 1.4 GHz)

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

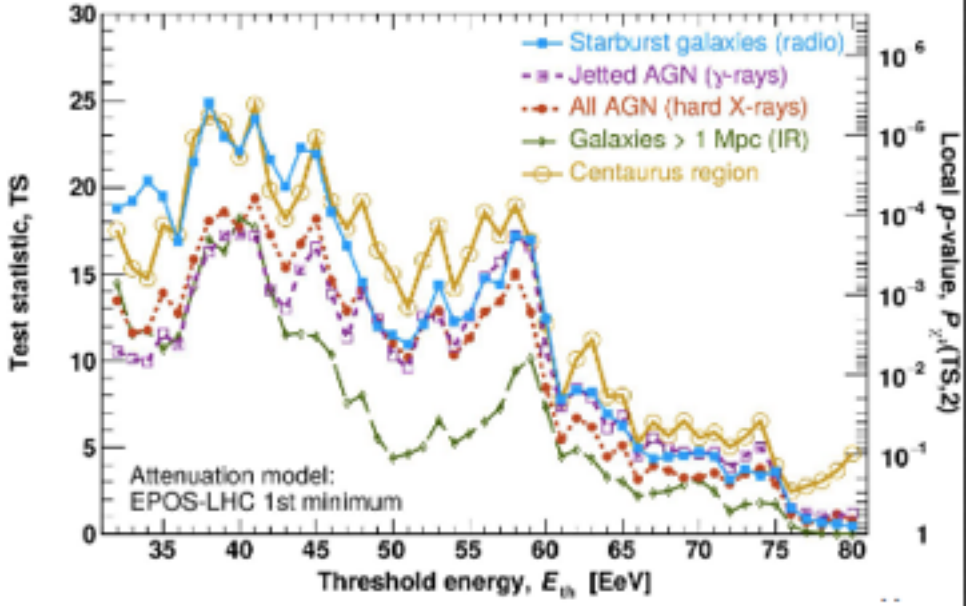
Catalog-based correlations

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]

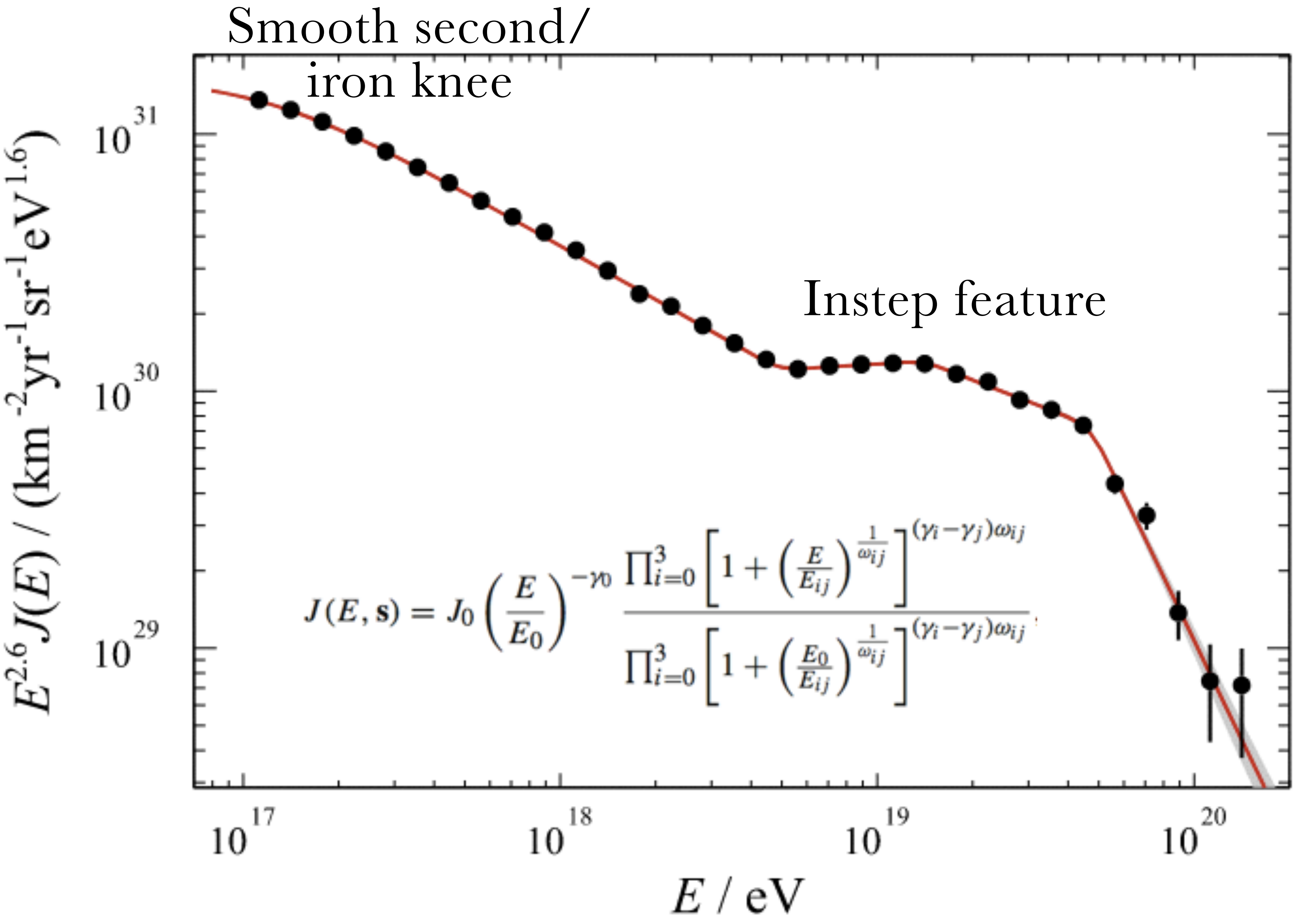
iii) Energy spectrum and mass composition: probing source properties

➡ Constraints on:

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

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

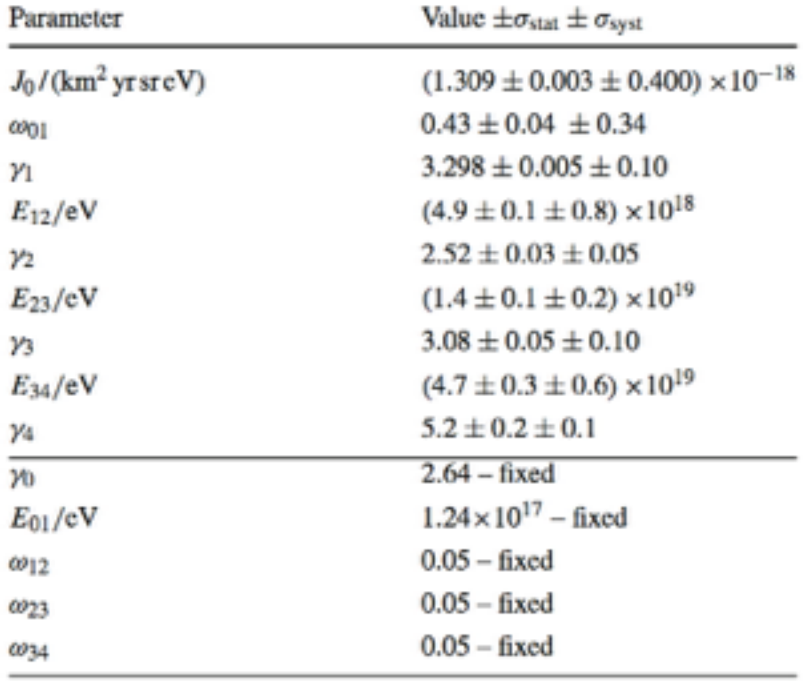
[EPJC 81 (2021) 966]



Smooth second/ iron knee

Instep feature

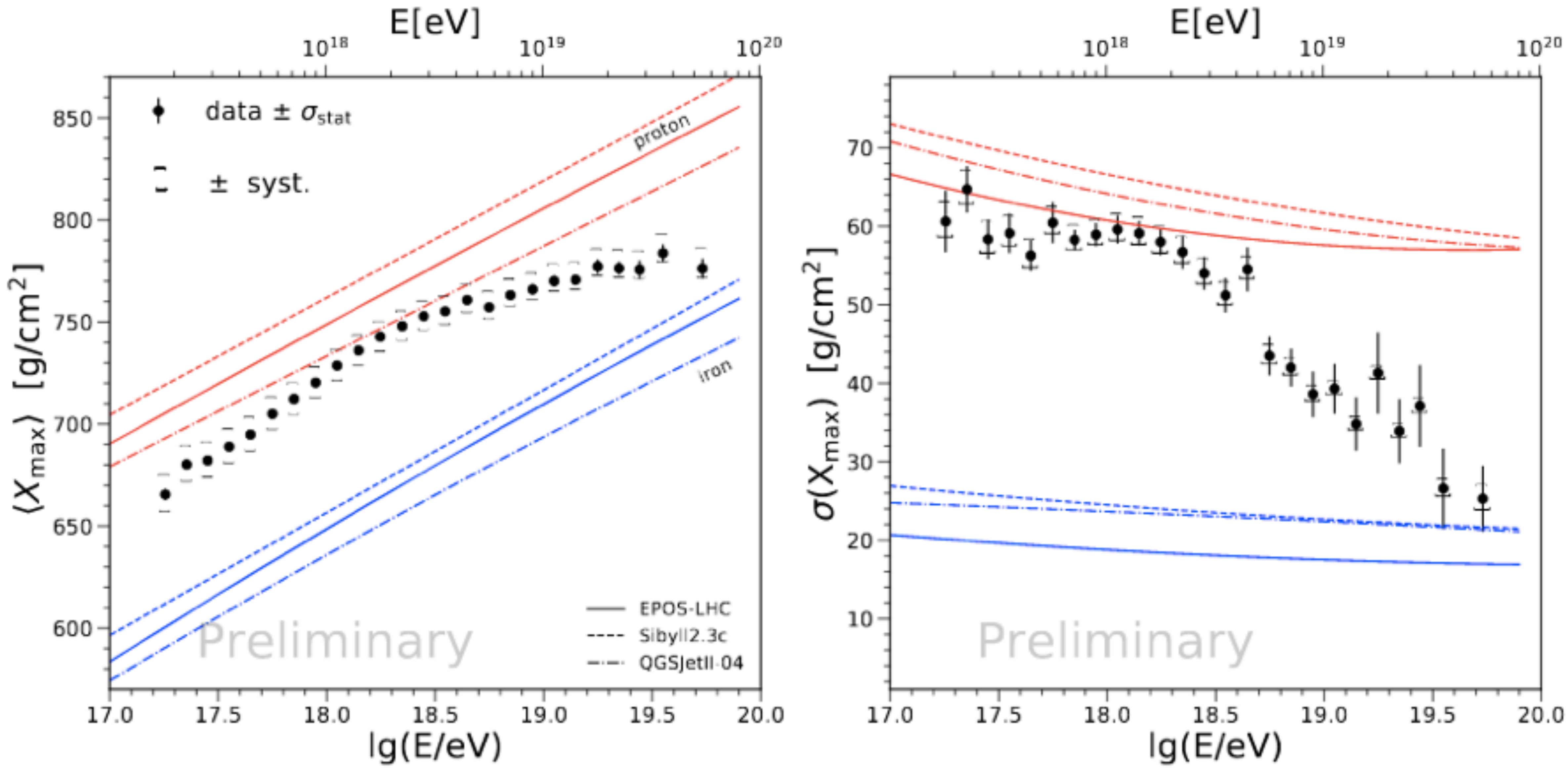
$$J(E, \mathbf{s}) = J_0 \left(\frac{E}{E_0}\right)^{-\gamma_0} \frac{\prod_{i=0}^{3} \left[1 + \left(\frac{E}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i - \gamma_j)\omega_{ij}}}{\prod_{i=0}^{3} \left[1 + \left(\frac{E_0}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i - \gamma_j)\omega_{ij}}}$$



Parameter	Value $\pm\sigma_{\rm stat} \pm \sigma_{\rm syst}$
$J_0/(\mathrm{km^2\,yr\,sr\,eV})$	$(1.309 \pm 0.003 \pm 0.400) \times 10^{-18}$
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

X_{max} moments

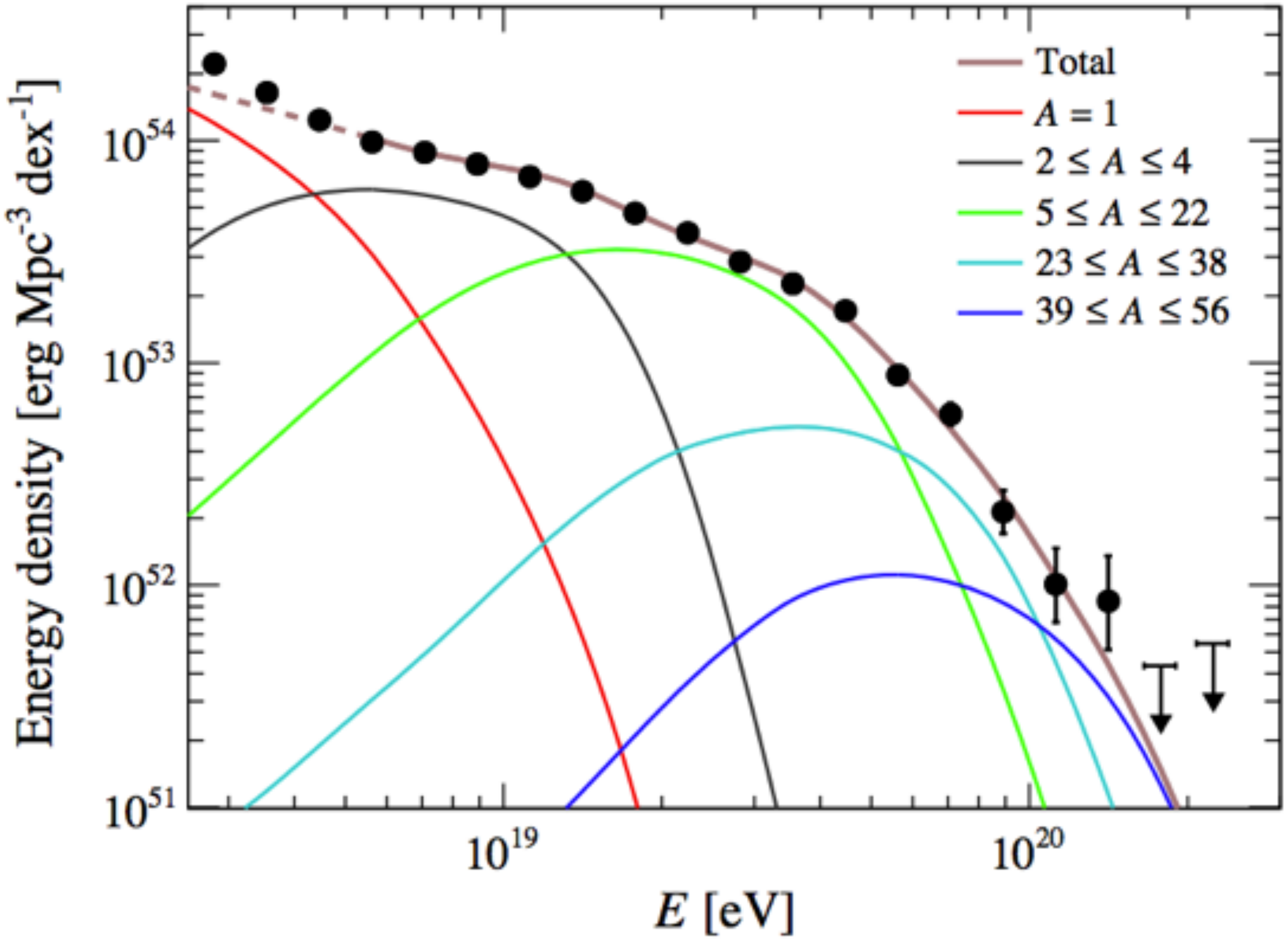
Above $E_0 \approx 2$ EeV both X_{max} moments are becoming compatible to MC predictions for heavier nuclei



[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) Astrophysical interpretations

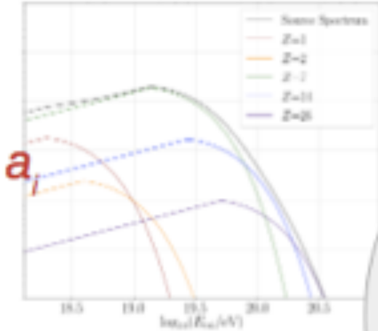
➡ A transient scenario to explain the correlation with star-forming galaxies?

Correlation with Star-forming Galaxies

- **homogeneous background**
  - with source evolution ~$(1+z)^m$
  - isotropic arrival directions
- **catalog sources: SBGs / AGNs**
  - flux weight & distance considered
  - arrival directions ~ Fisher
    → turb. magnetic field blurring

$$\delta_S = \delta_0 \, Z_{\mathrm{det}} \, \frac{10\ \mathrm{EeV}}{E_{\mathrm{det}}}$$

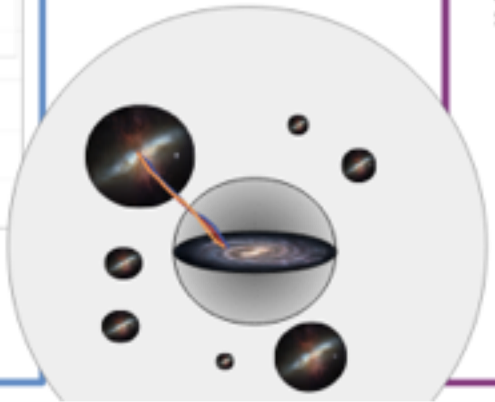
- **injection:** power law + exp. cutoff
  - spectral index γ, rigidity cutoff R_{cut}, element fractions a_i

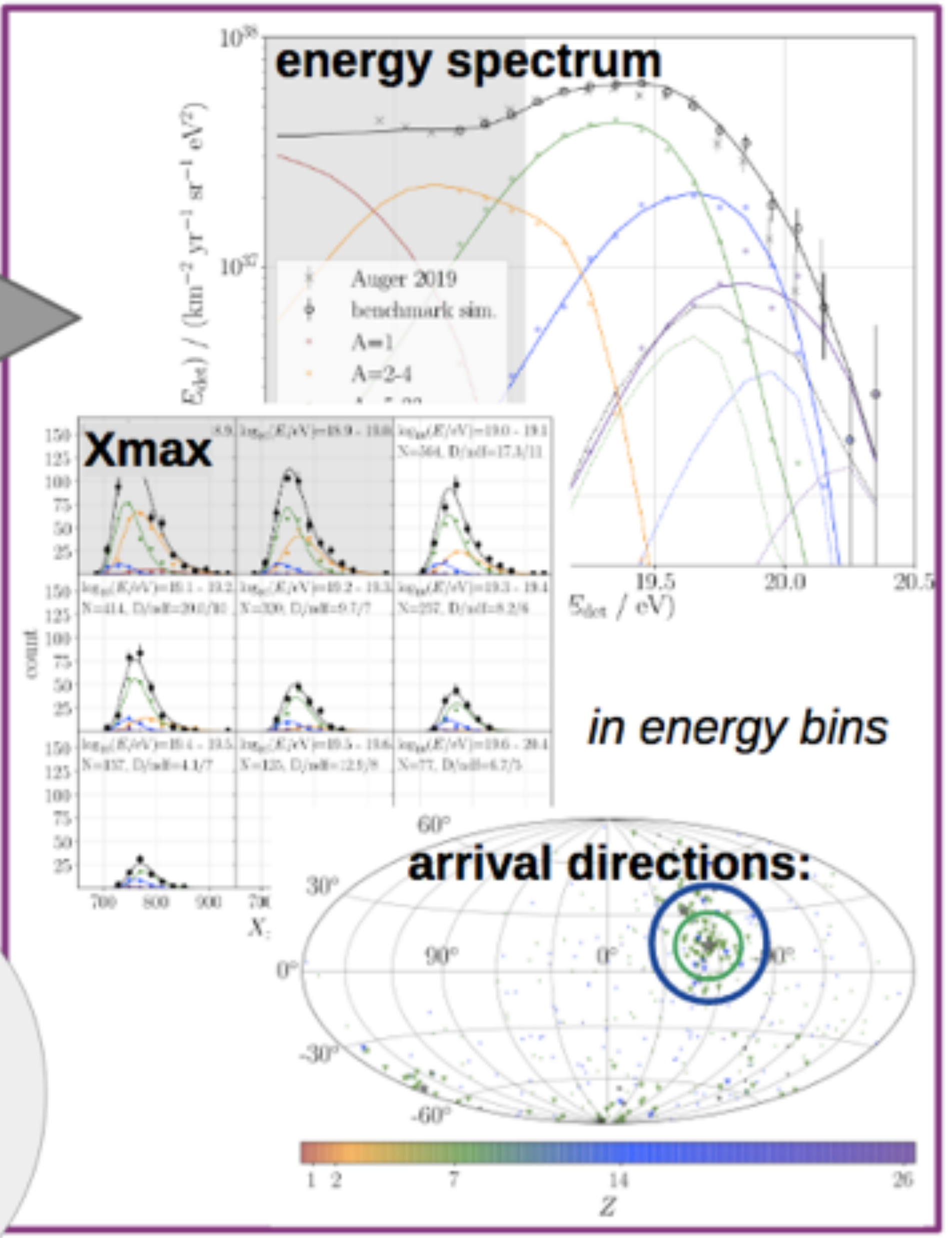


add above $10^{18.7}$ eV:
f_0 * catalog+ (1-f_0) * background

propagation

1d **CRPropa3** simulations
+
reweighting



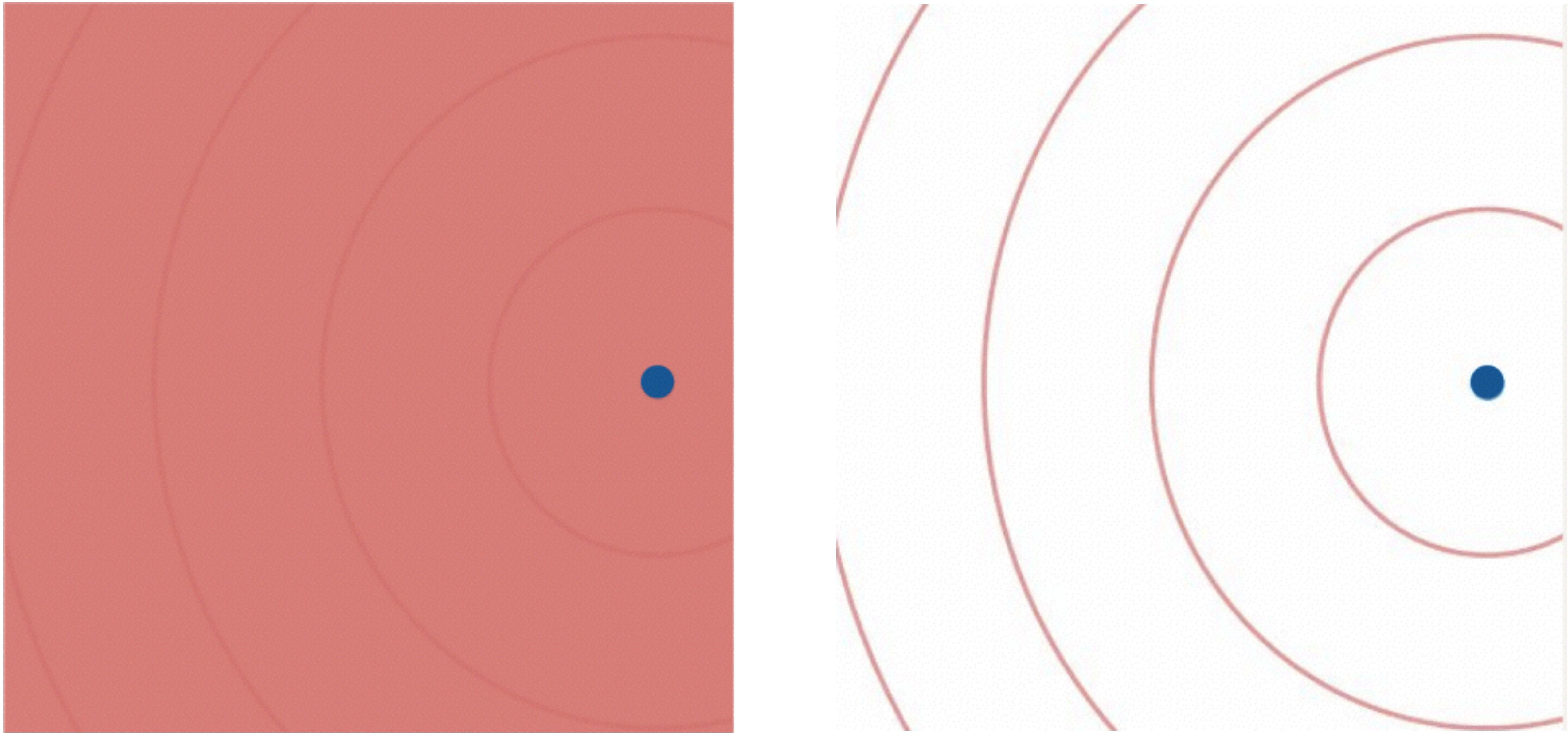


✦ 4.5 sigma with star-forming galaxies

[JCAP, submitted]

Steady state/Transient state

- Starburst galaxies responsible for 15% of the SFR (for $z<2$)
- Transient sources in every star-forming galaxy?



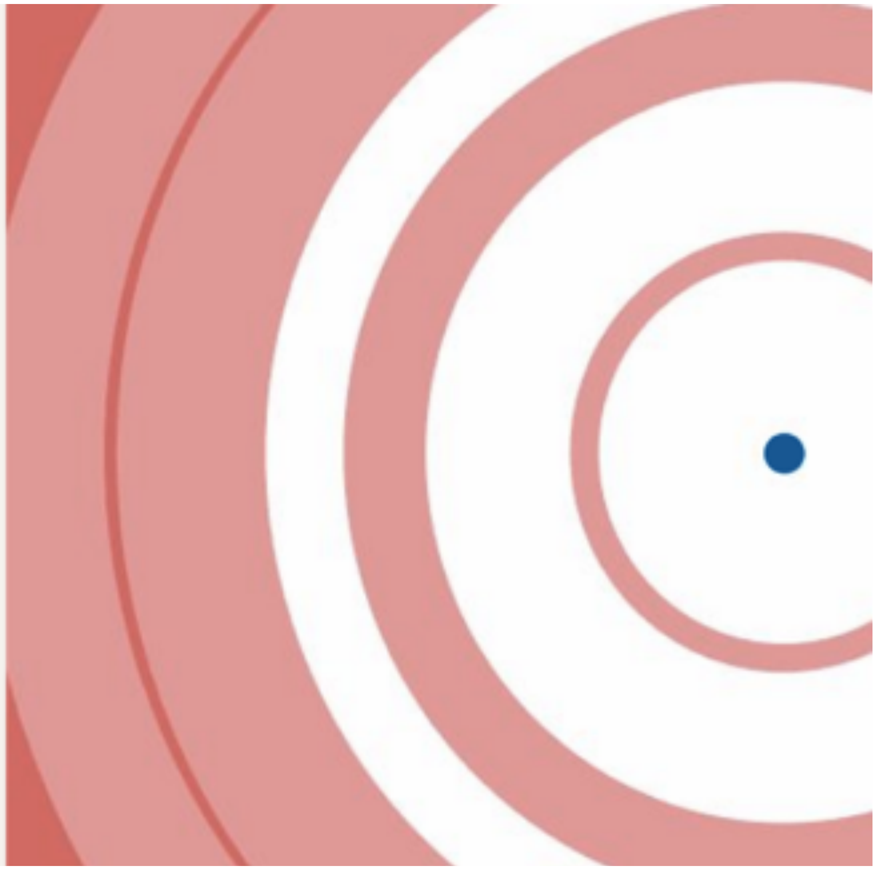
From transient to steady states

- ➔ Transient scenario
  - UHECRS produced per burst lasting a time ε

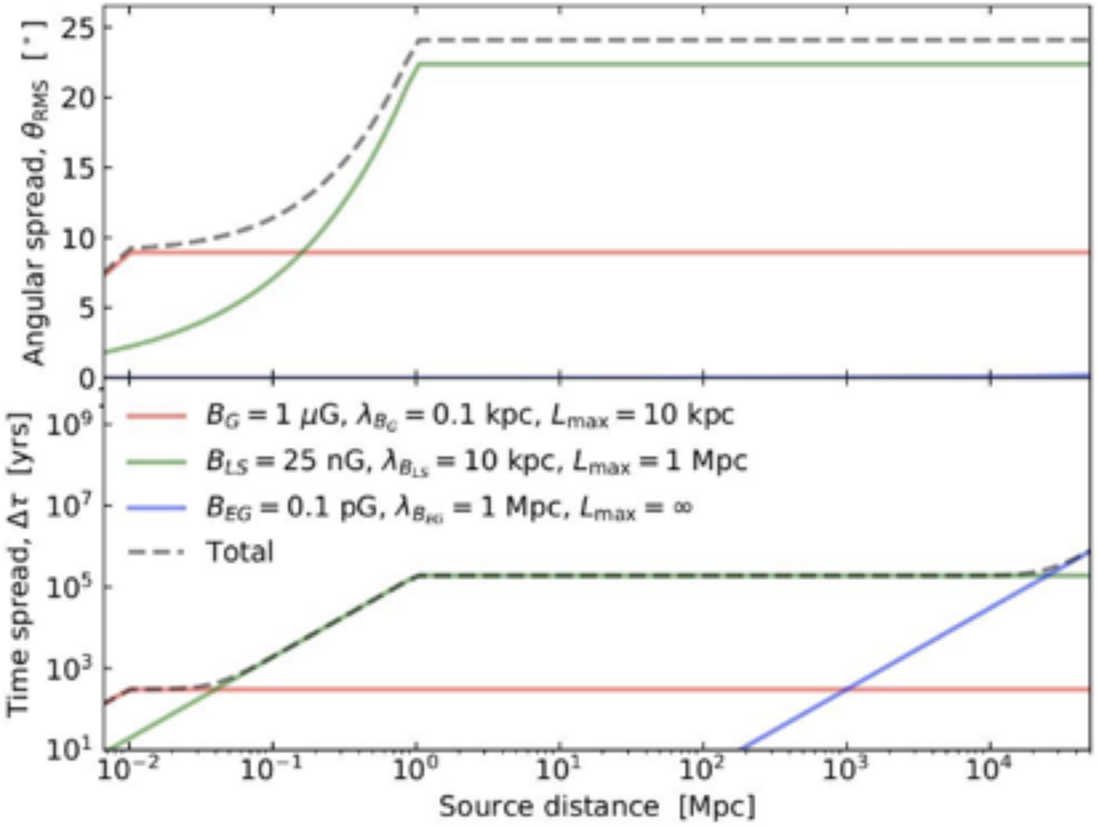
● Source bursting

🟥 UHECR burst

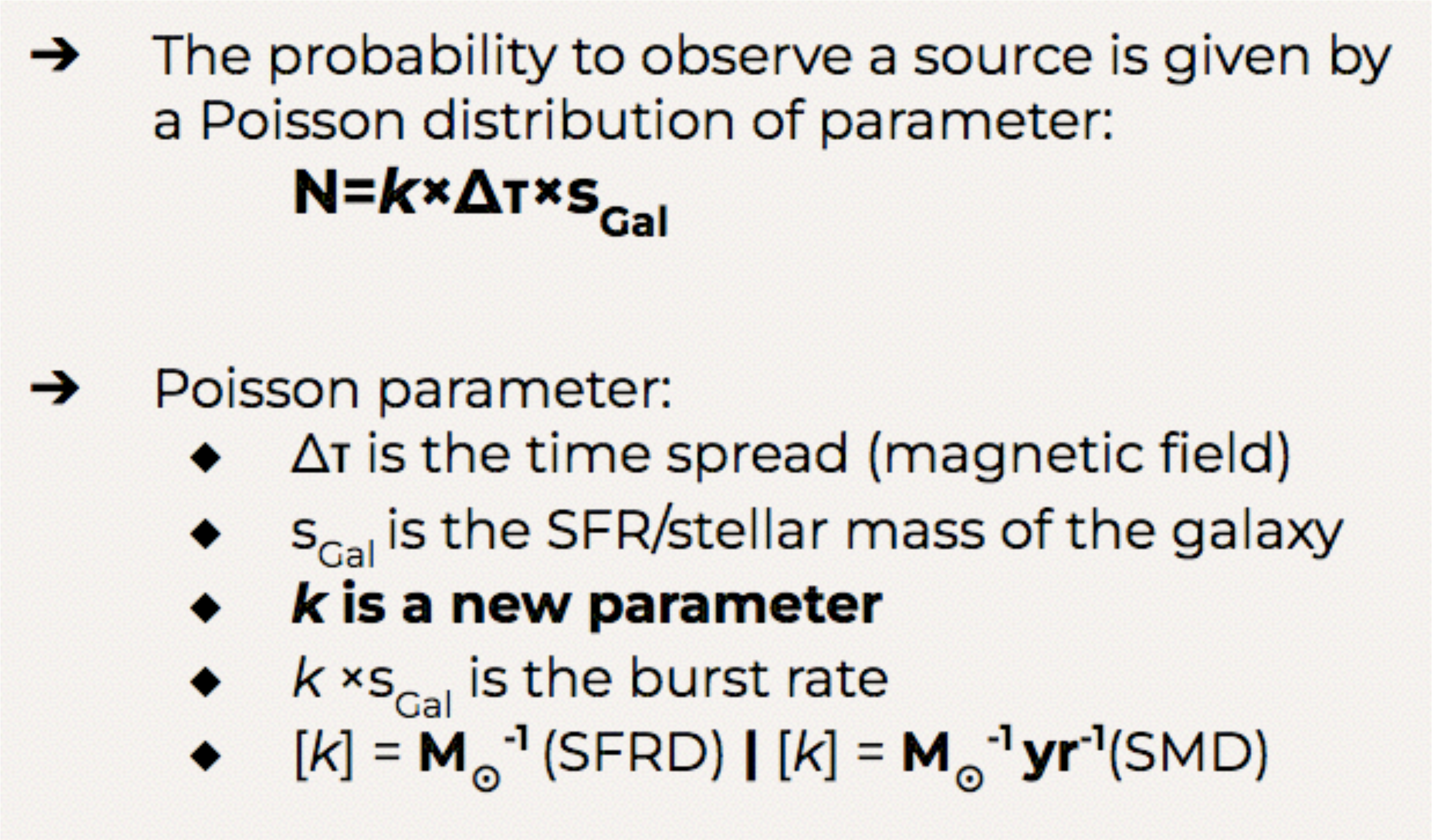
- ➔ Magnetic field
  - Time spread of the burst induced by the magnetic field



- ➔ Galactic magnetic field (JF12)
  - Strength B_G = 1 μG
  - Coherence length λ_G = 0.1 kpc
  - Size L_{max} = 10 kpc
- ➔ **Local Sheet magnetic field**
  - Strength B_G = [10; 25] nG (at least few nG, **consistent with MHD simulation**, considering primordial origin)
  - Coherence length λ_G = 10 kpc
  - Size L_{max} = 1 Mpc
- ➔ Extragalactic magnetic field
  - Strength B_G = 0.1 pG
  - Coherence length λ_G = 1 Mpc
  - Size L_{max} = ∞



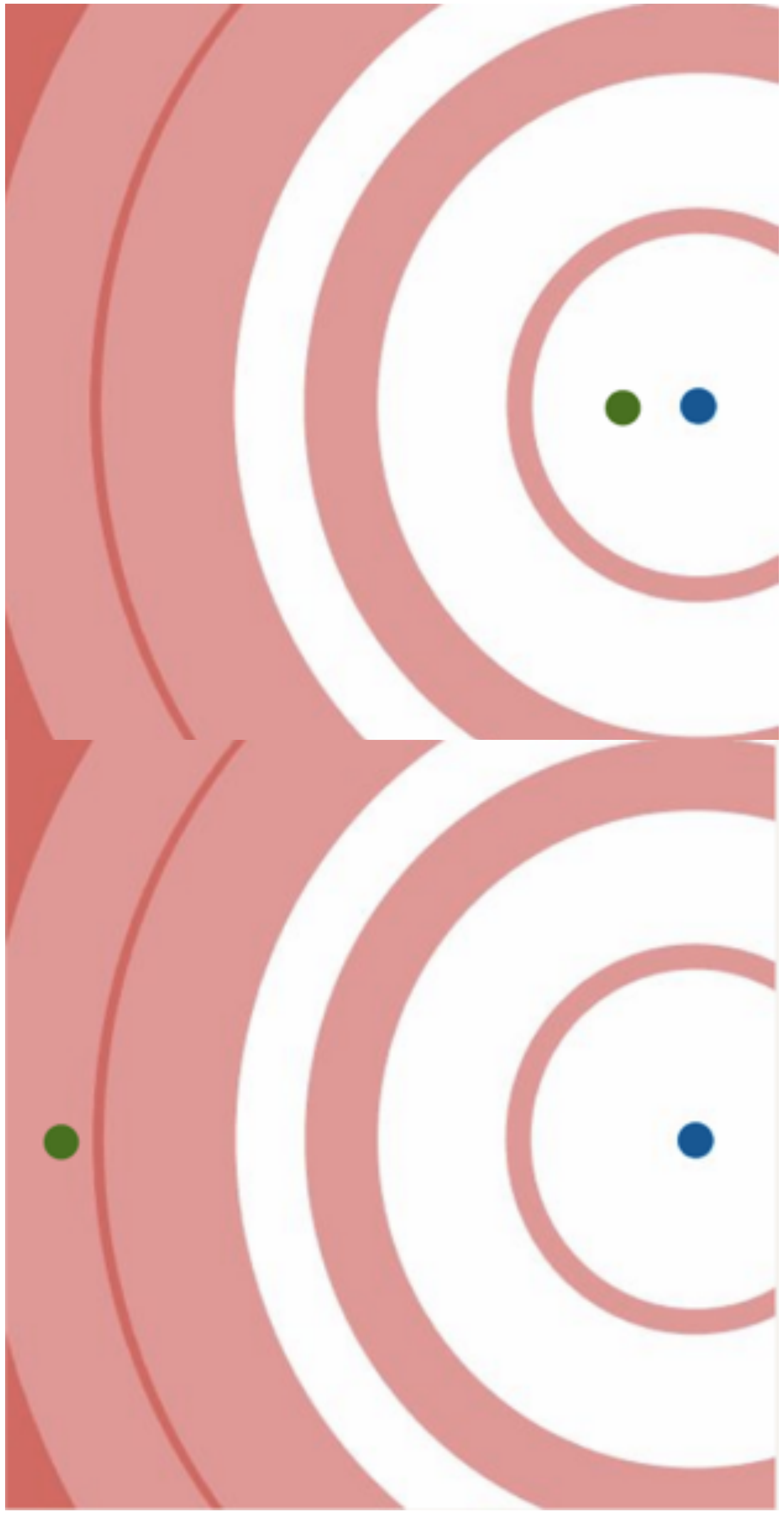
Testing the transient scenario for UHECRs



- ➔ The probability to observe a source is given by a Poisson distribution of parameter:

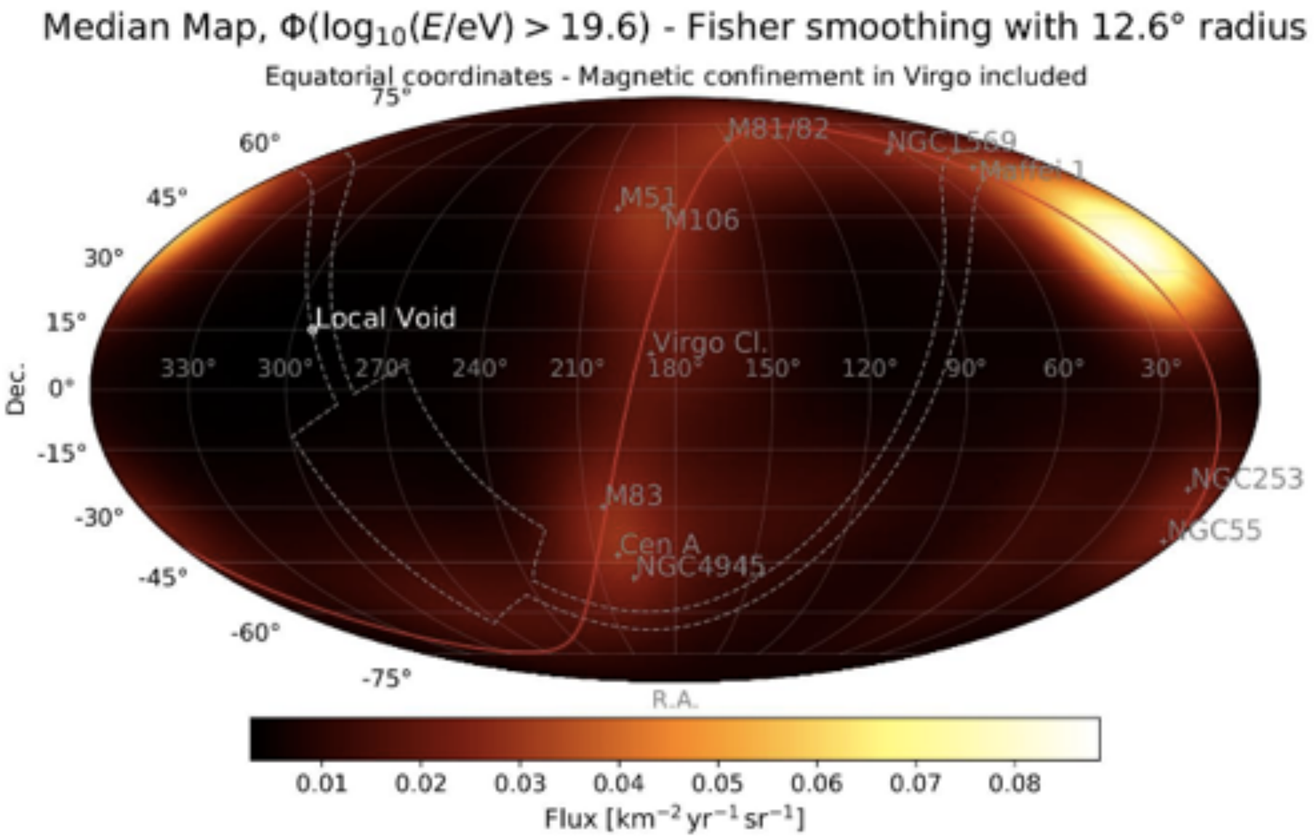
  $$\mathbf{N = \mathit{k} \times \Delta\tau \times s_{Gal}}$$

- ➔ Poisson parameter:
  - $\Delta\tau$ is the time spread (magnetic field)
  - s_{Gal} is the SFR/stellar mass of the galaxy
  - ***k*** **is a new parameter**
  - $k \times s_{Gal}$ is the burst rate
  - $[k] = \mathbf{M_{\odot}}^{-1}$ (SFRD) **|** $[k] = \mathbf{M_{\odot}}^{-1}\mathbf{yr}^{-1}$(SMD)



Median (SFR) map — Small and high *k* values

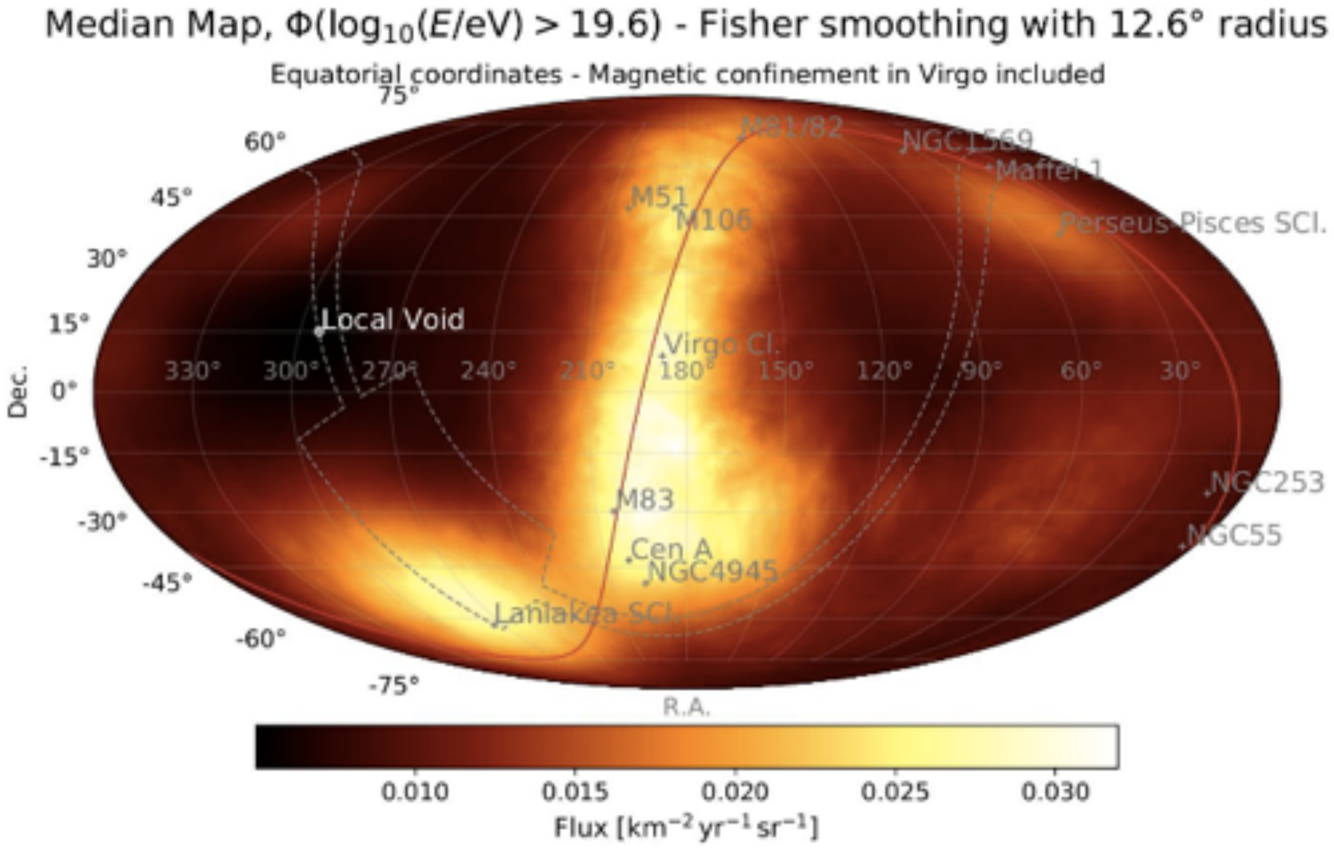
- Here, $k=10^{-4}\ M_{\odot}^{-1}$
- Median map
- Council of Giants contributes
- Nearby galaxies as Andromeda dominate the UHECR sky



Median Map, $\Phi(\log_{10}(E/\mathrm{eV}) > 19.6)$ - Fisher smoothing with 12.6° radius

Equatorial coordinates - Magnetic confinement in Virgo included

- Here, $k=10^{-7}\ M_{\odot}^{-1}$
- Median map
- Council of Giants **does not** contribute !
- Dominated by far-away clusters/superclusters

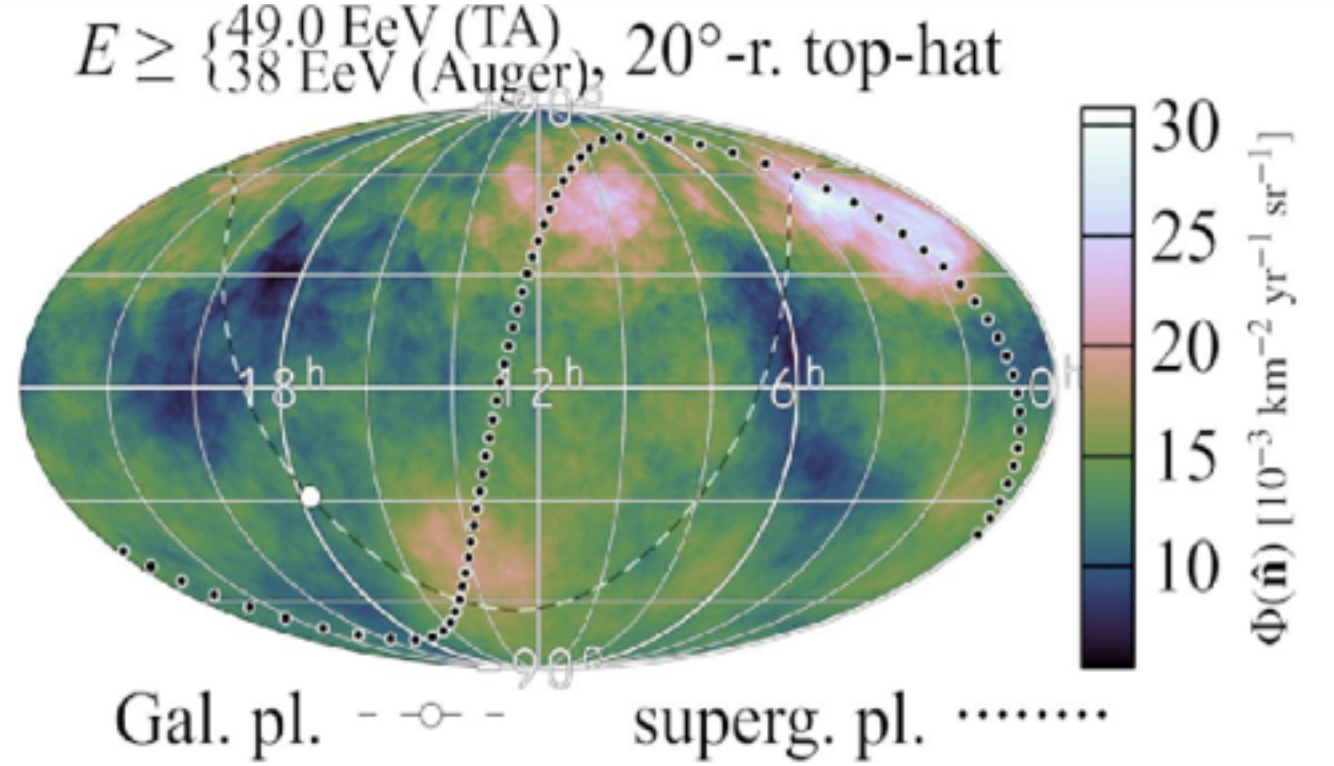


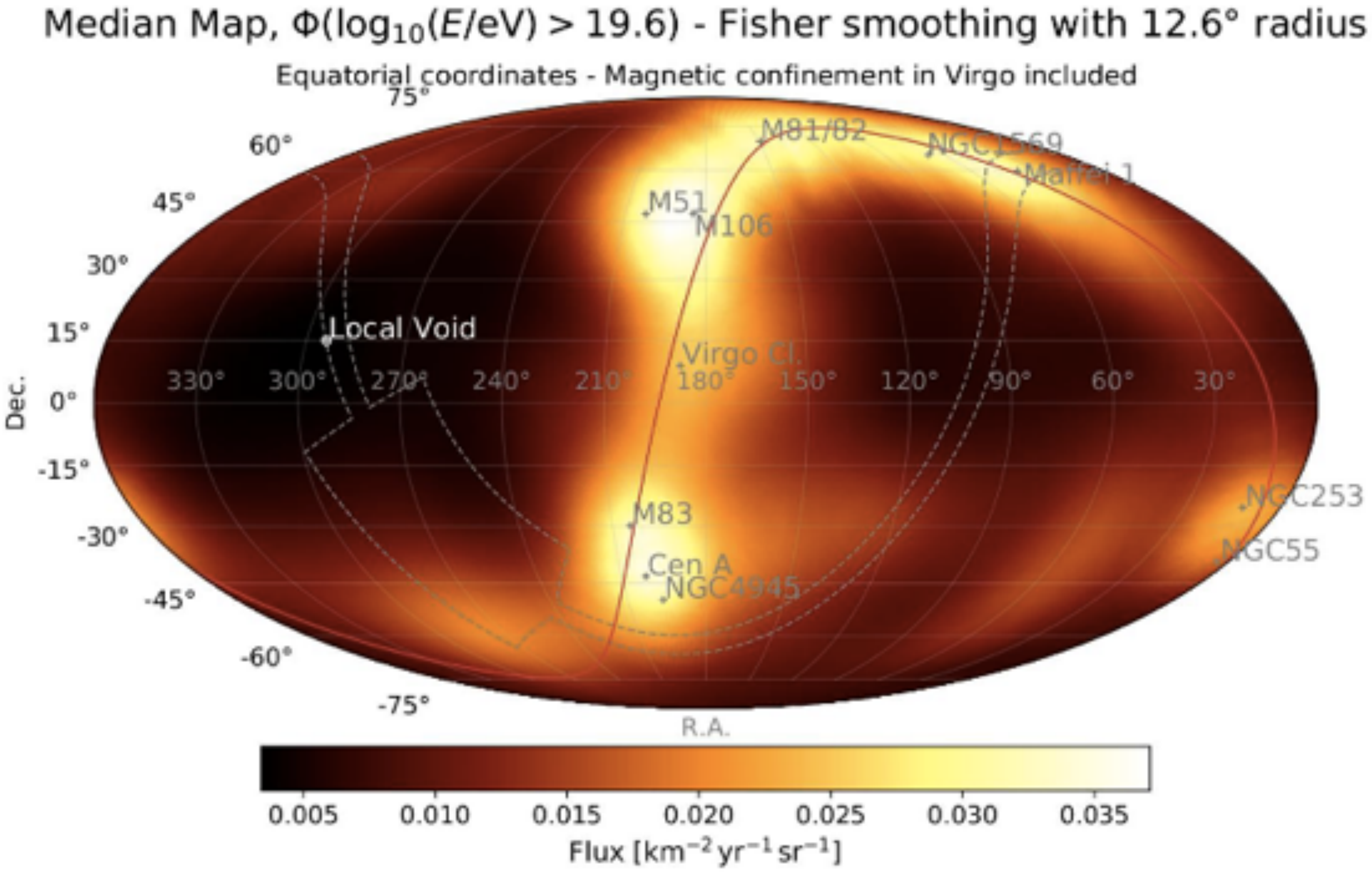
Median Map, $\Phi(\log_{10}(E/\mathrm{eV}) > 19.6)$ - Fisher smoothing with 12.6° radius

Equatorial coordinates - Magnetic confinement in Virgo included

Median (SFR) map — Best *k*

- Here, $\boldsymbol{k=10^{-5}\,M_\odot^{-1}}$
- Median map
- Council of Giants contributes
- No contribution from very close galaxies

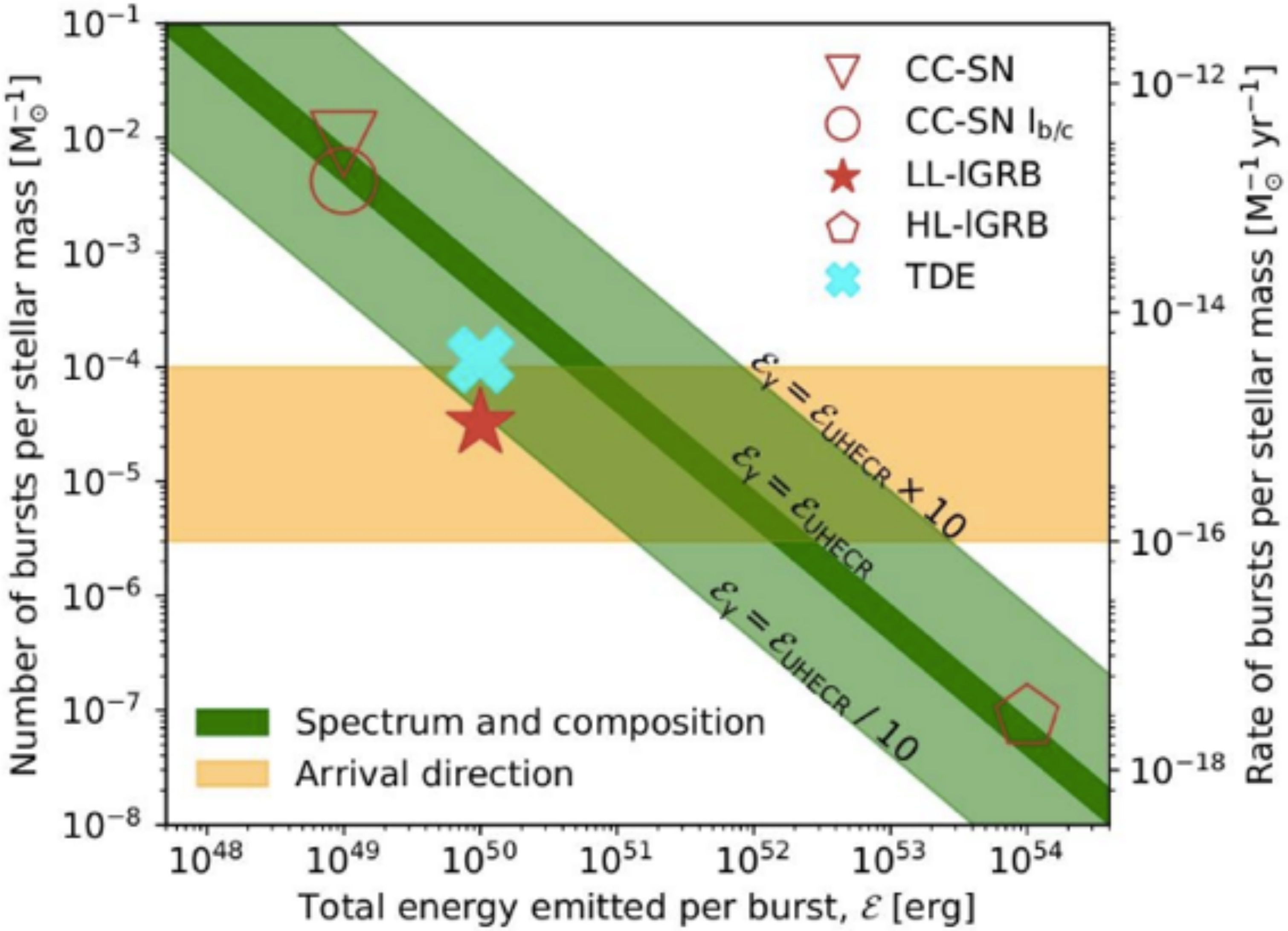




[Marafico et al., in preparation]

Constraints on sources

- ➔ SFRD scenario:
  - Core Collapse supernova (CC-SN)
  - CC-SN type Ib/c
  - Low luminosity lGRB (LL-lGRB)
  - High luminosity lGRB(HL-lGRB)
- ➔ SMD scenario:
  - Tidal Disruption Event (TDE)
- ➔ Two sources reach the two requirements:
  - LL-lGRB
  - TDE

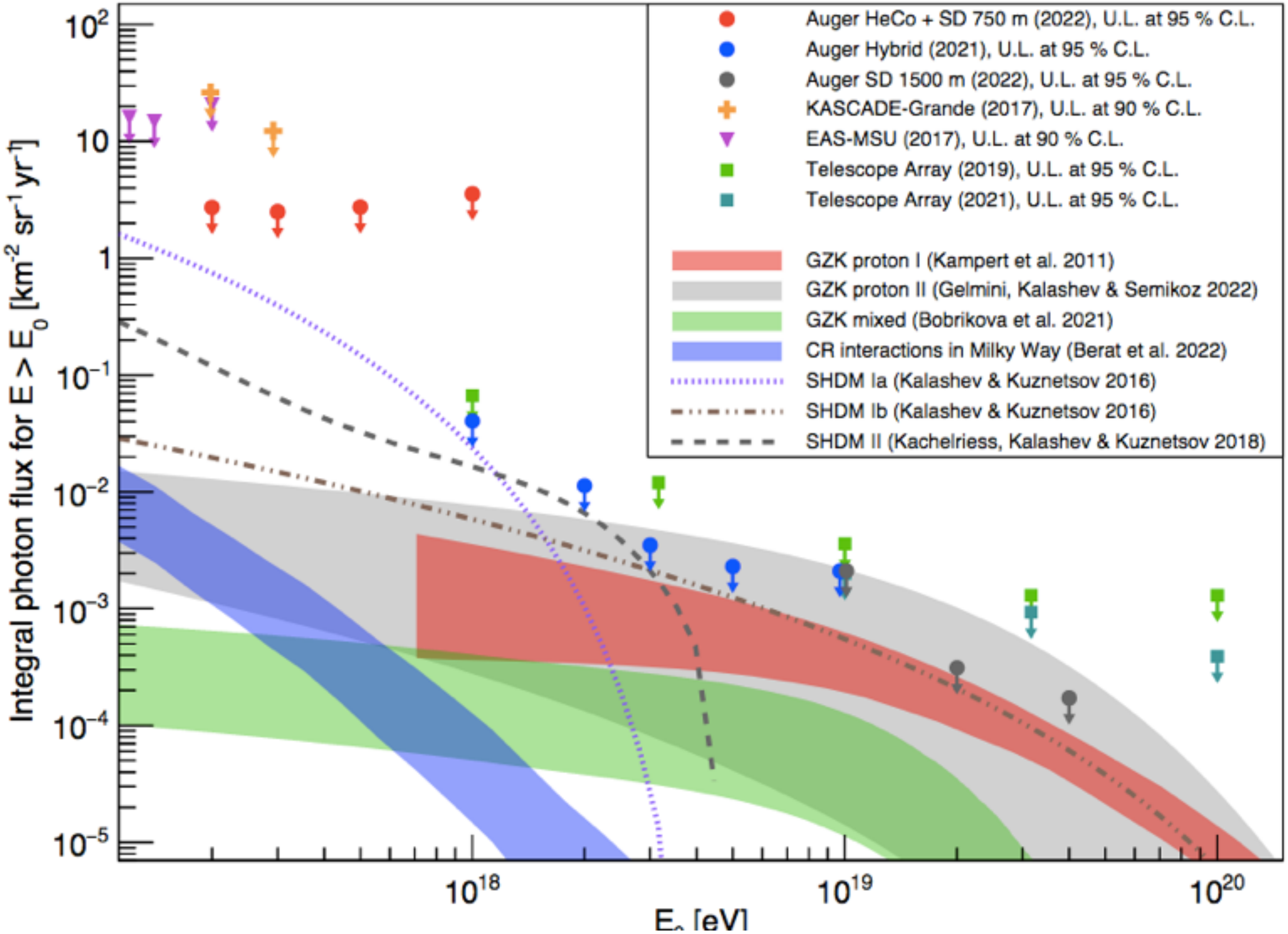


[Marafico et al., in preparation]

v) Photons, neutrinos, multi-messenger, BSM, (super-heavy) dark matter

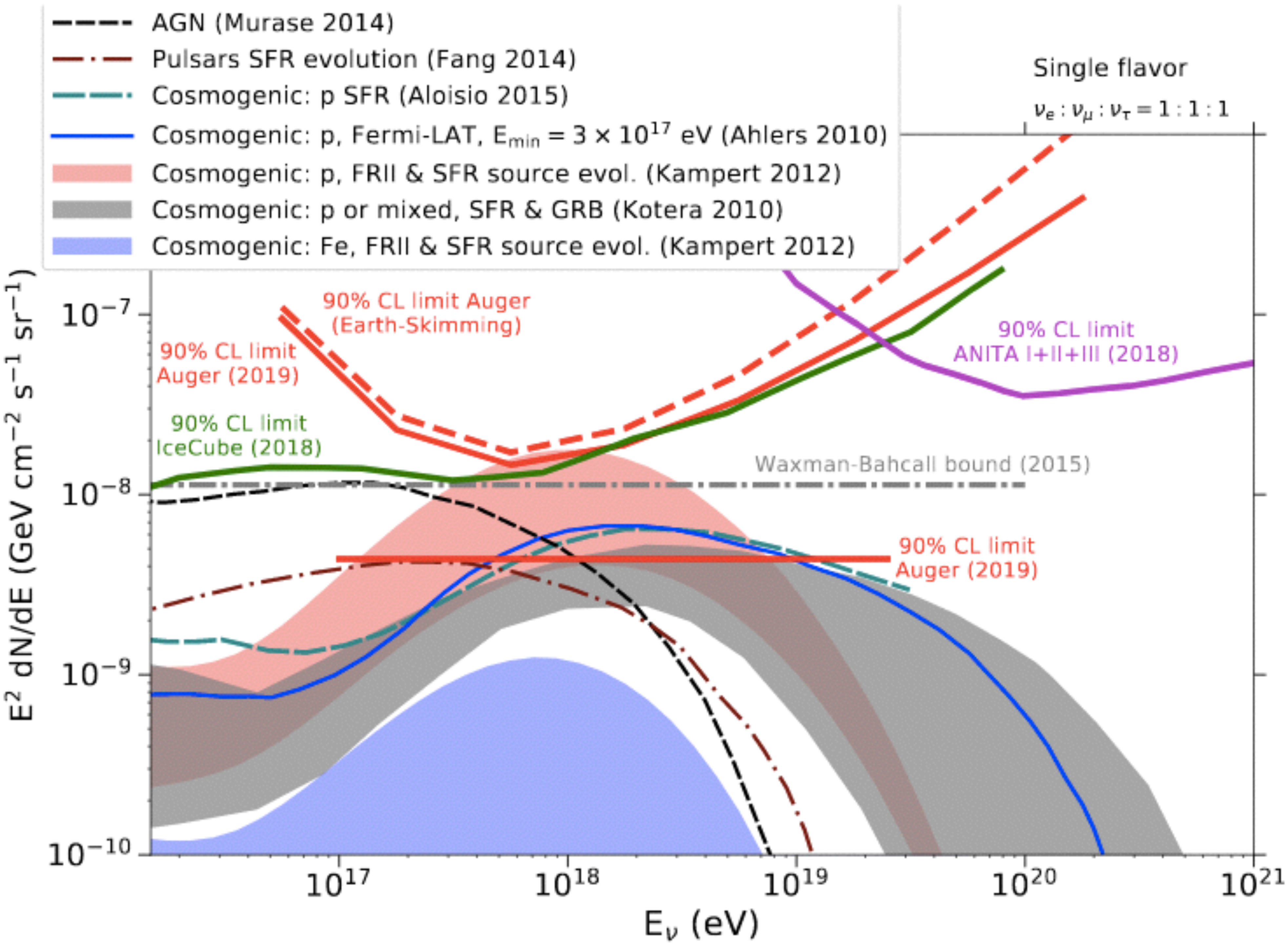
« Une fourmi parlant français
Parlant latin et javanais
Ça n'existe pas ça n'existe pas
Et pourquoi pas ? » **R. Desnos**

Limits on photon fluxes



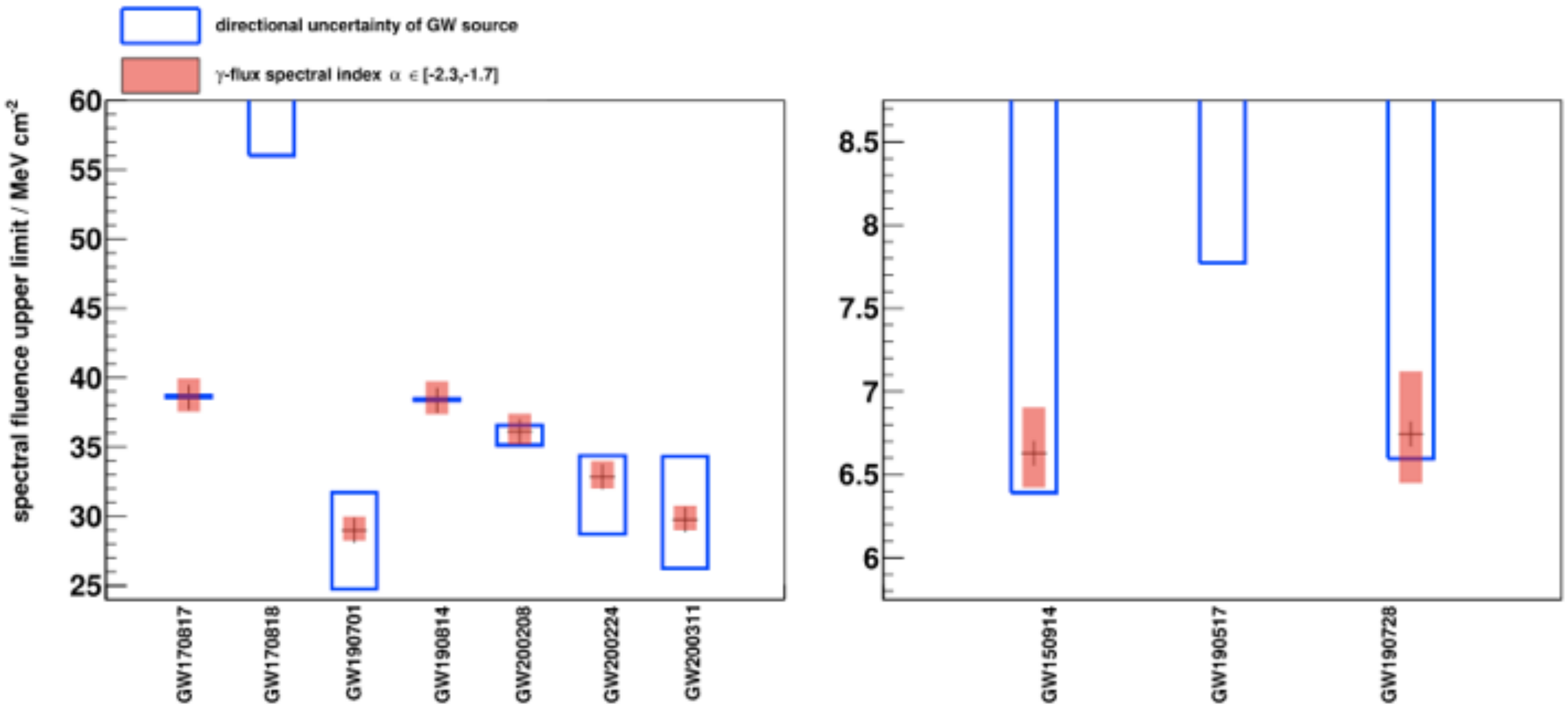
[ApJ 933 (2022) 125]

Limits on neutrino fluxes



[JCAP 10 (2019) 022]

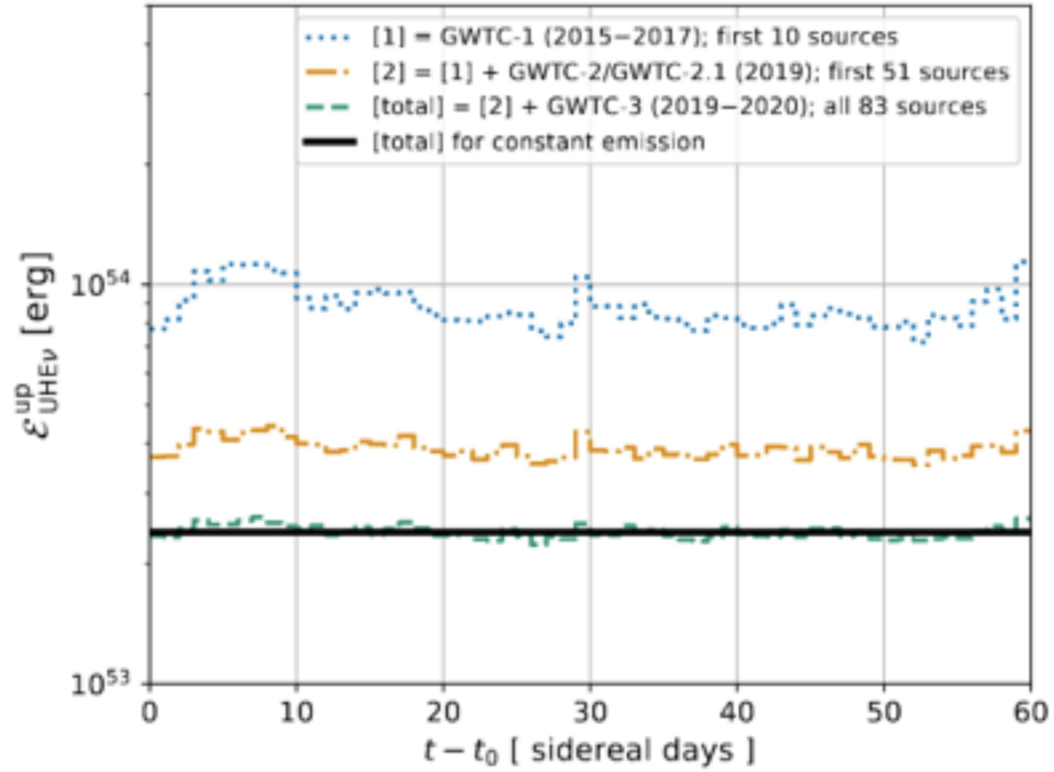
Correlations with GW?



(a)

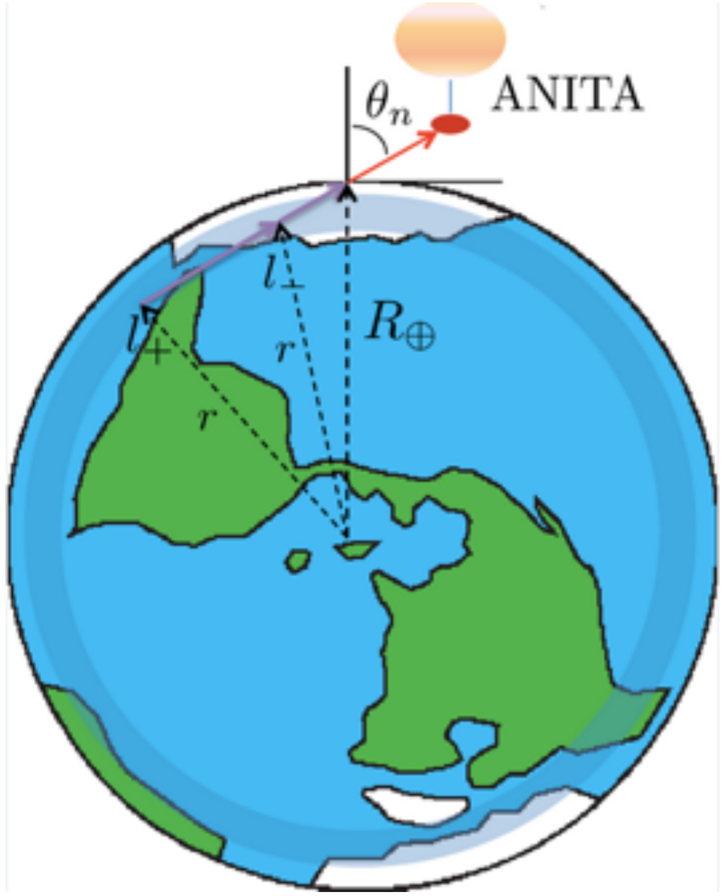
(b)

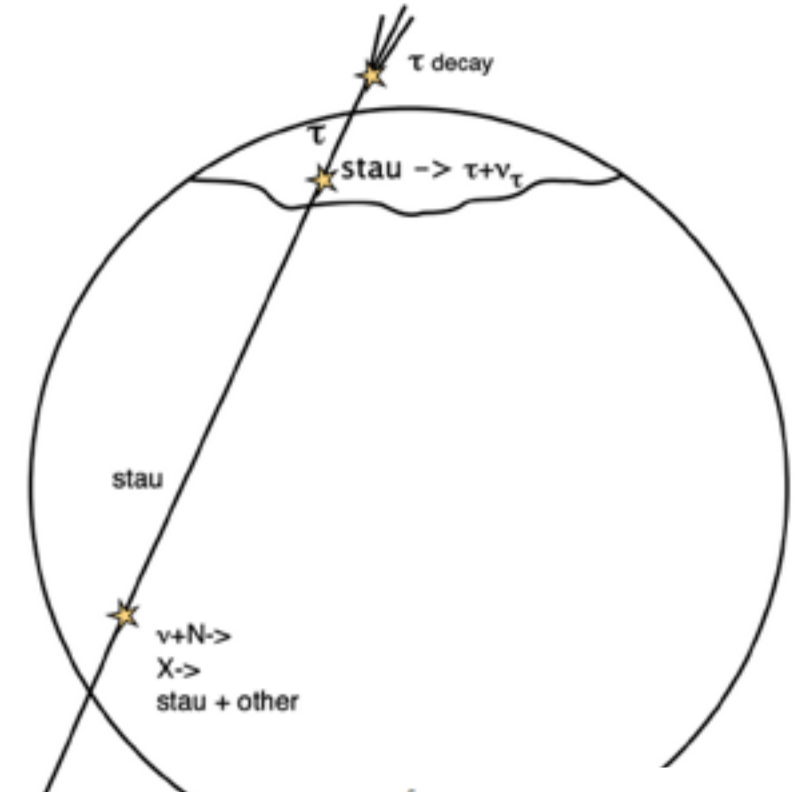
[ApJ, in press]

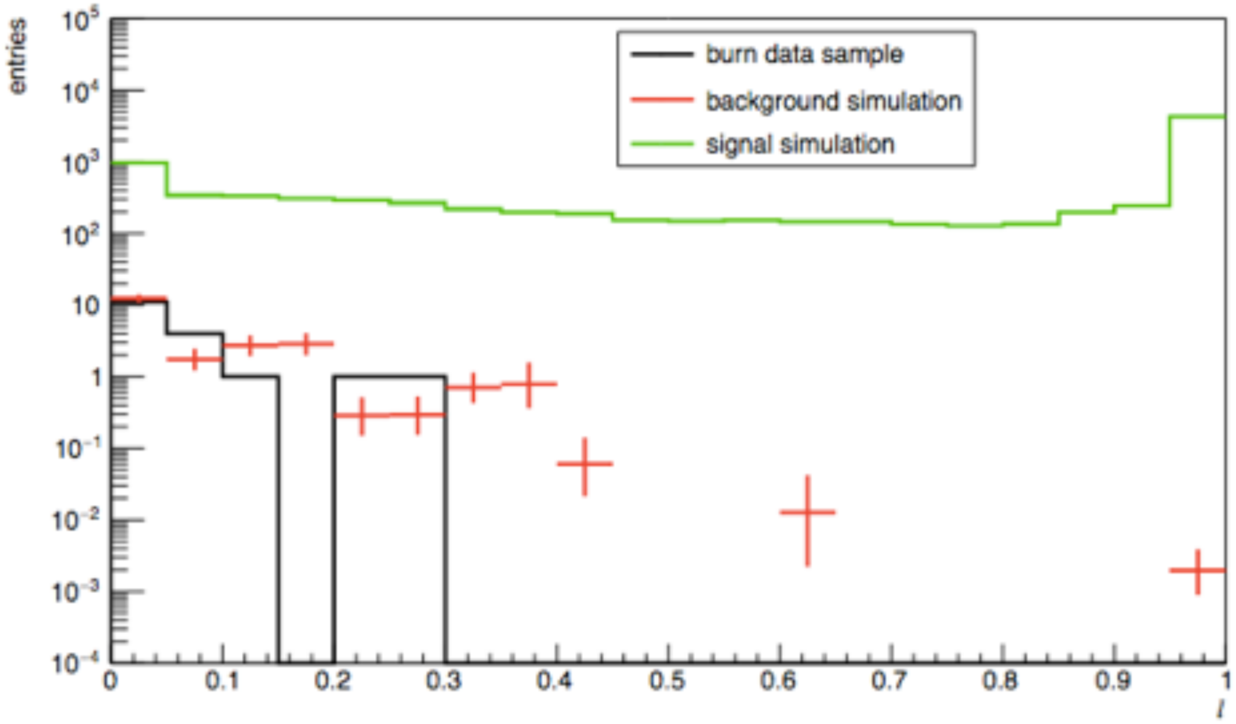


Anomalous ANITA events

- ✦ Earth-skimming neutrinos
- ✦ A few anomalous events







- ✦ Searches for upgoing showers
- ✦ Stringent upper limits

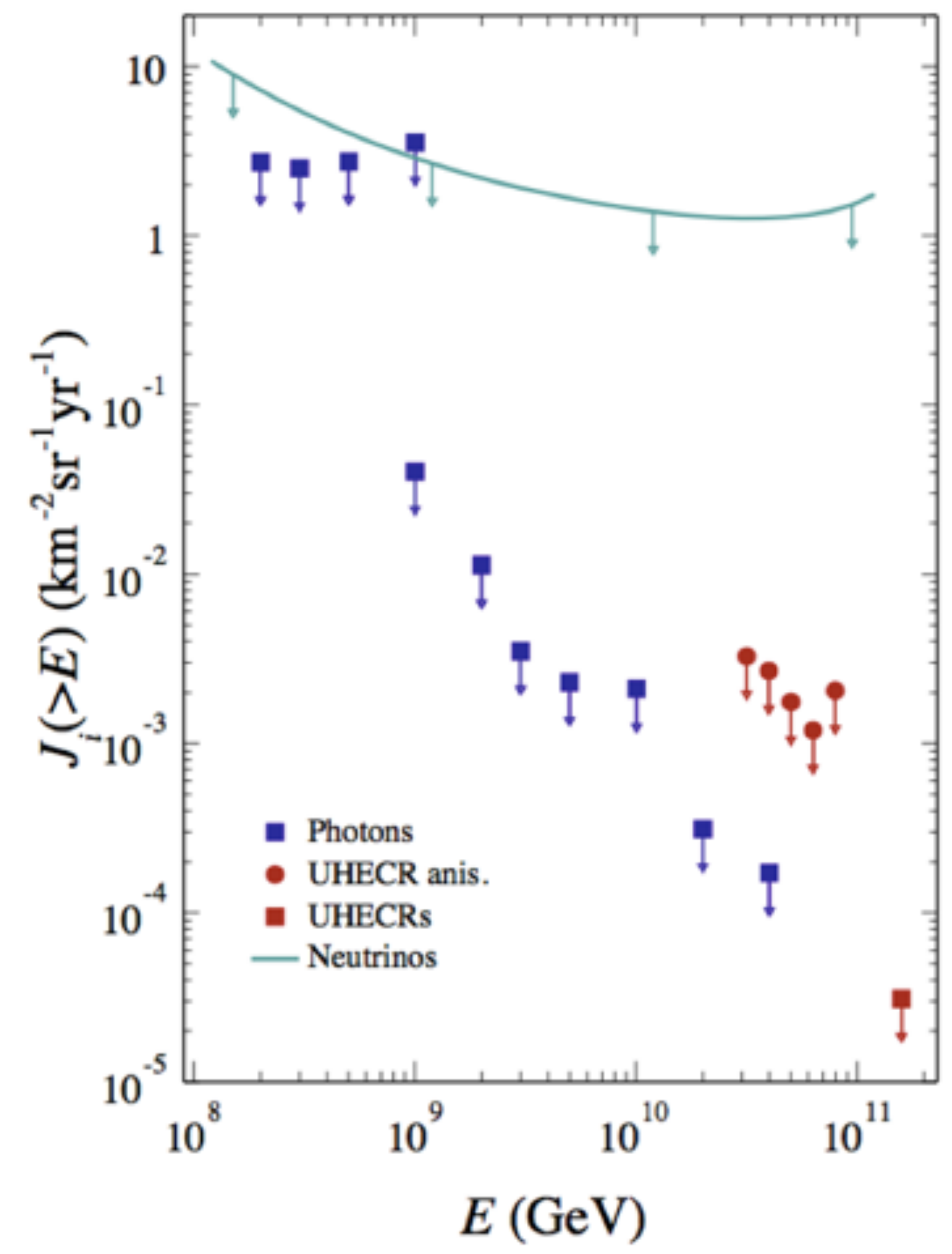
[PRL, in preparation]

Secondary by-product fluxes from SDHM decay

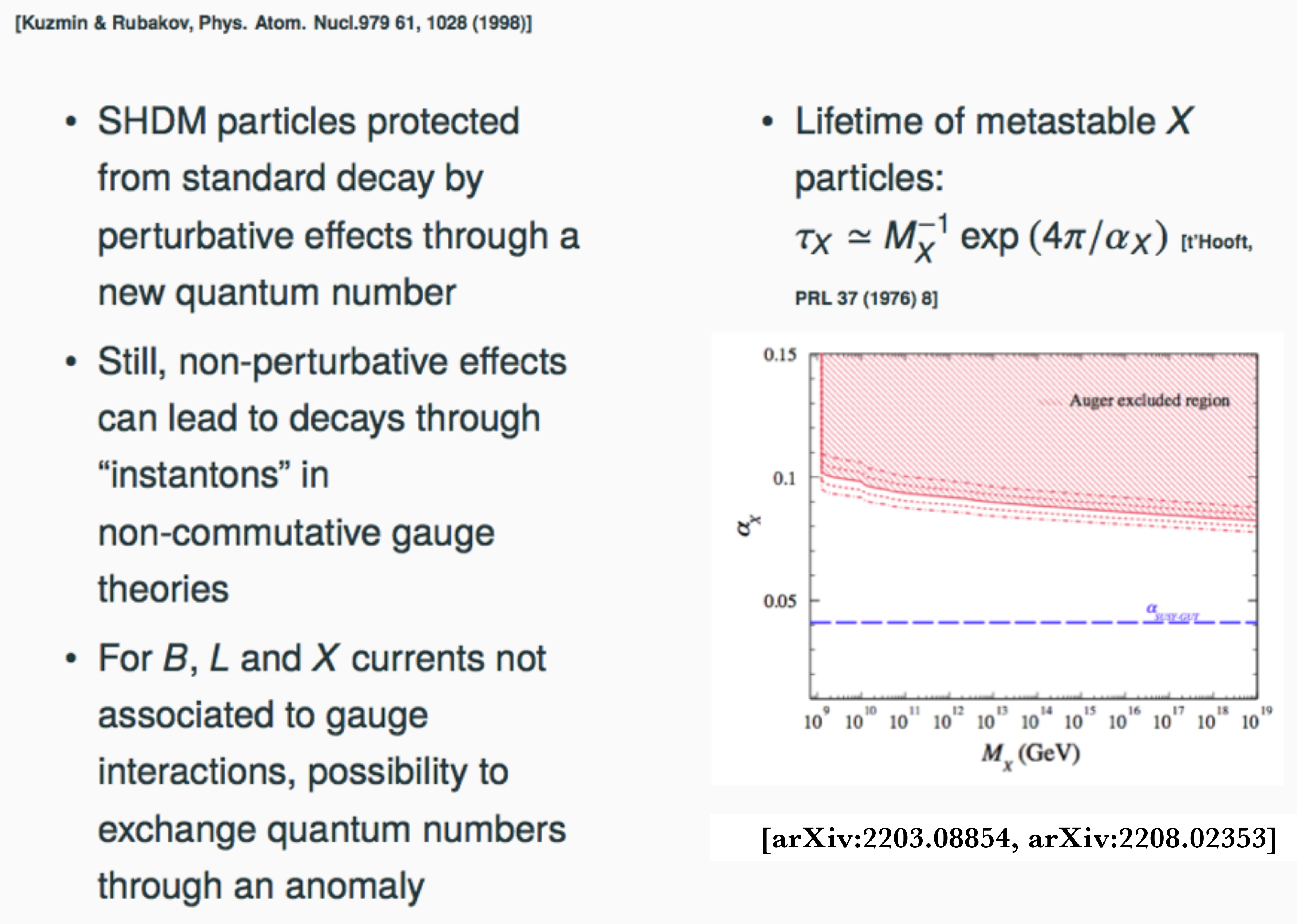
- Flux of secondaries from SHDM decay ($i = \gamma, \nu, \overline{\nu}, N, \overline{N}$):

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

- ρ_{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

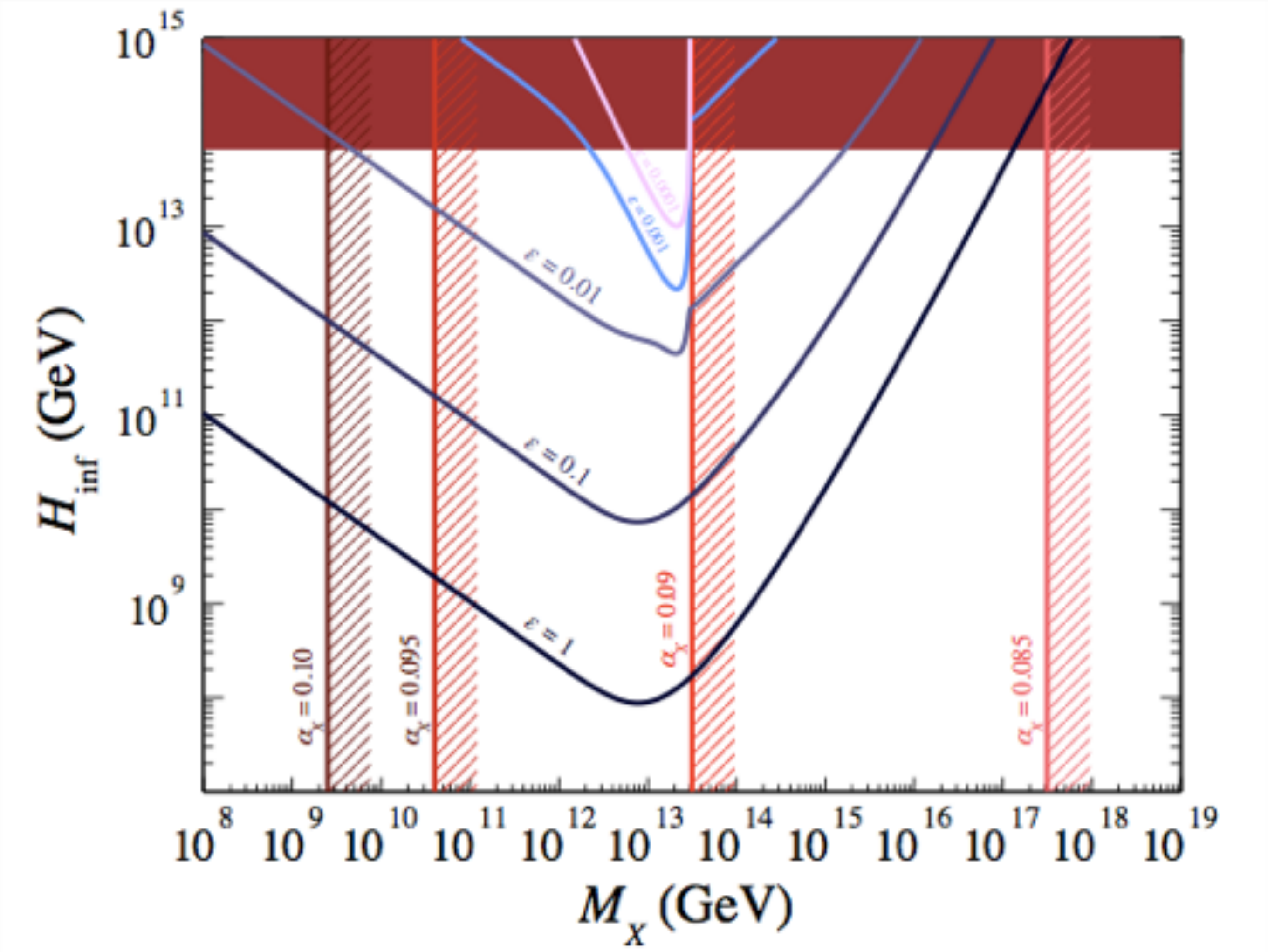
- Lifetime of metastable X particles: $\tau_X \simeq M_X^{-1} \exp\left(4\pi/\alpha_X\right)$ [t'Hooft, PRL 37 (1976) 8]

[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]

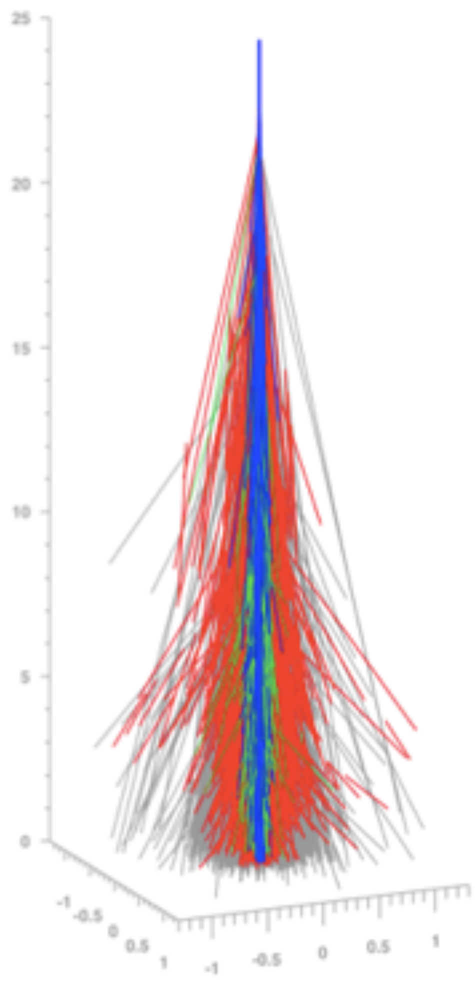


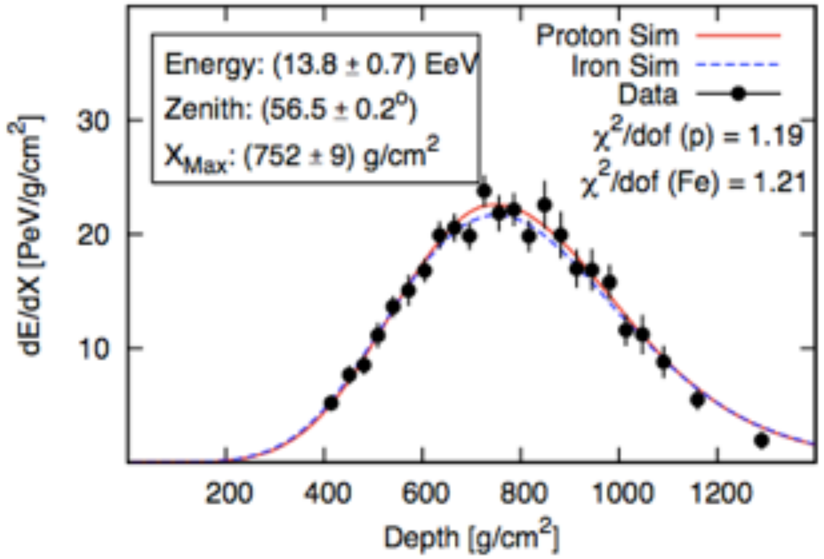
- GUT mass scale viable for $\epsilon \to 1$ ($T_{\rm rh}$ relatively high) $\implies$ tensor/scalar ratio r of the primordial modes possibly detectable in the CMB
- For $\epsilon \leq 0.01$, 10^{13} GeV mass scale viable, testable for $\alpha_X \lesssim 0.09$

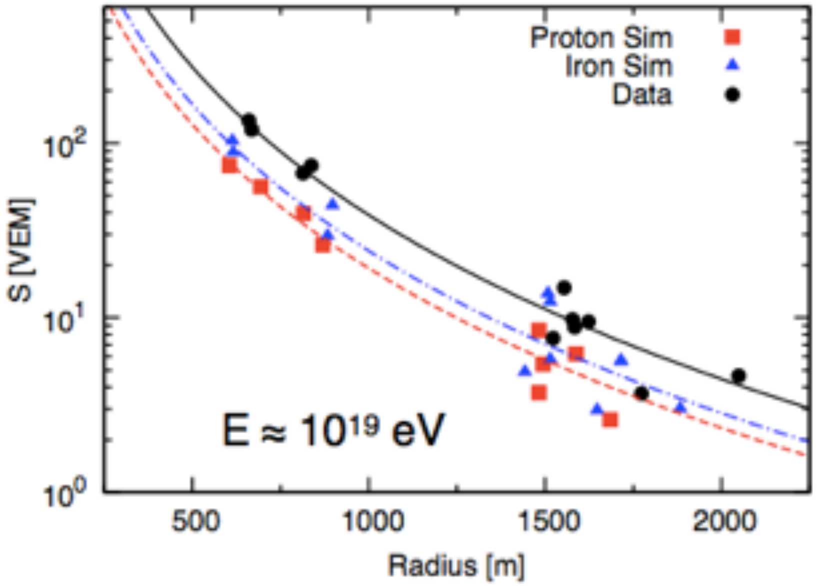
vi) Puzzles in extensive air showers

« 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



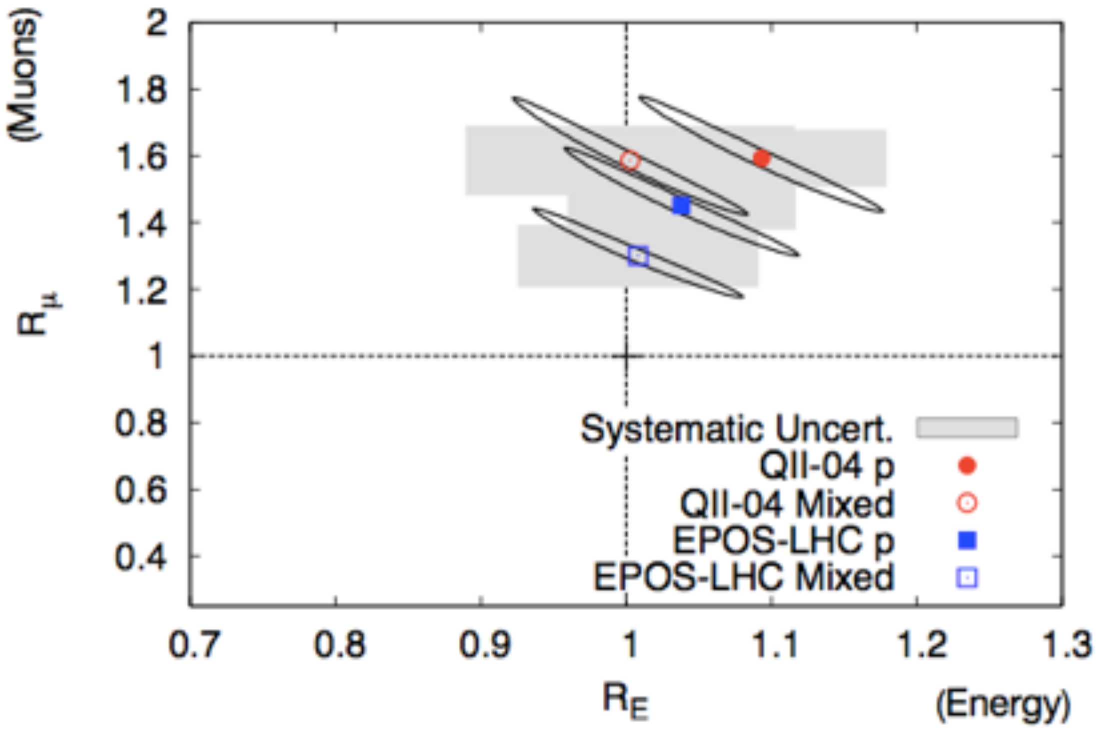




Phenomenological model ansatz

Energy scaling: em. particles and muons

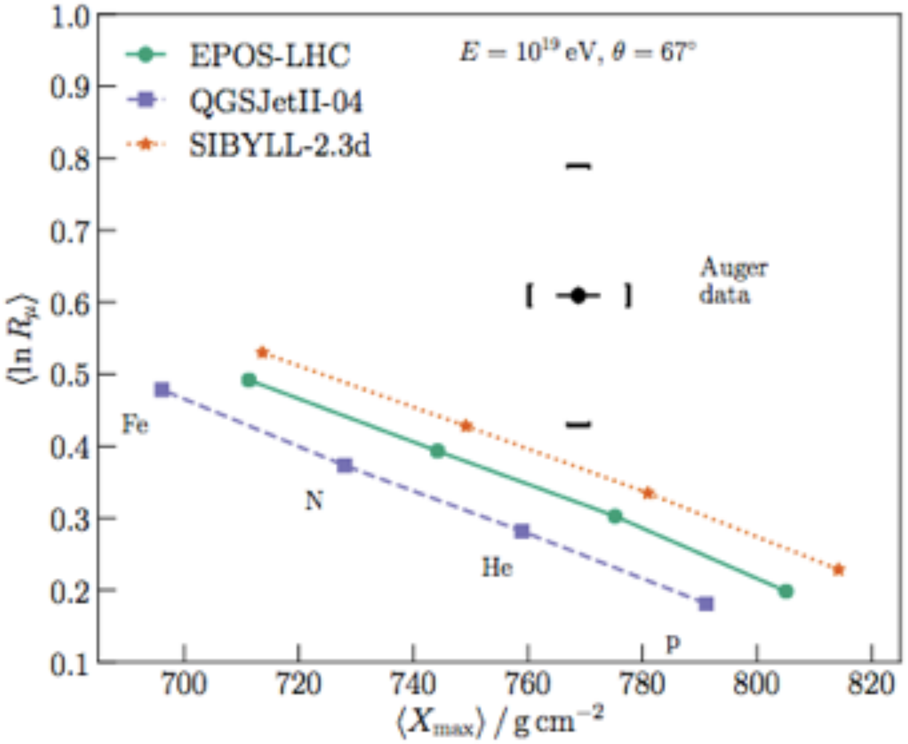
Muon scaling: hadronically produced muons and muon interaction/decay products



[PRL, 117 (2016) 192001]

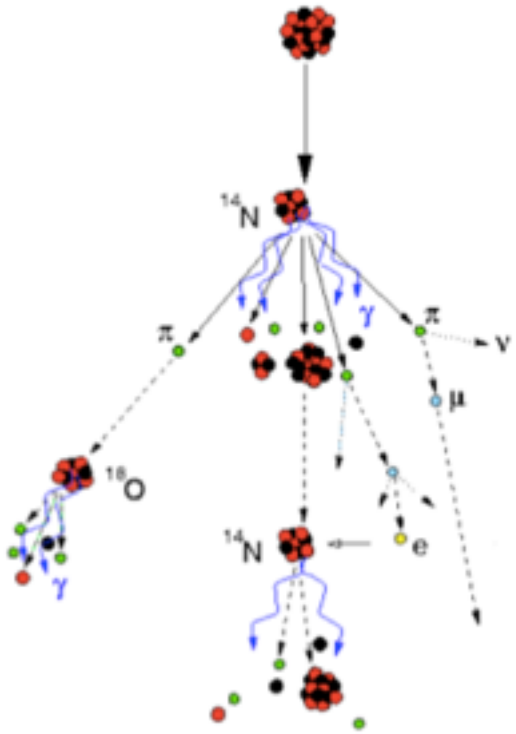
Muon number in inclined showers (θ > 60°)

[PRL, 126 (2021) 152002]

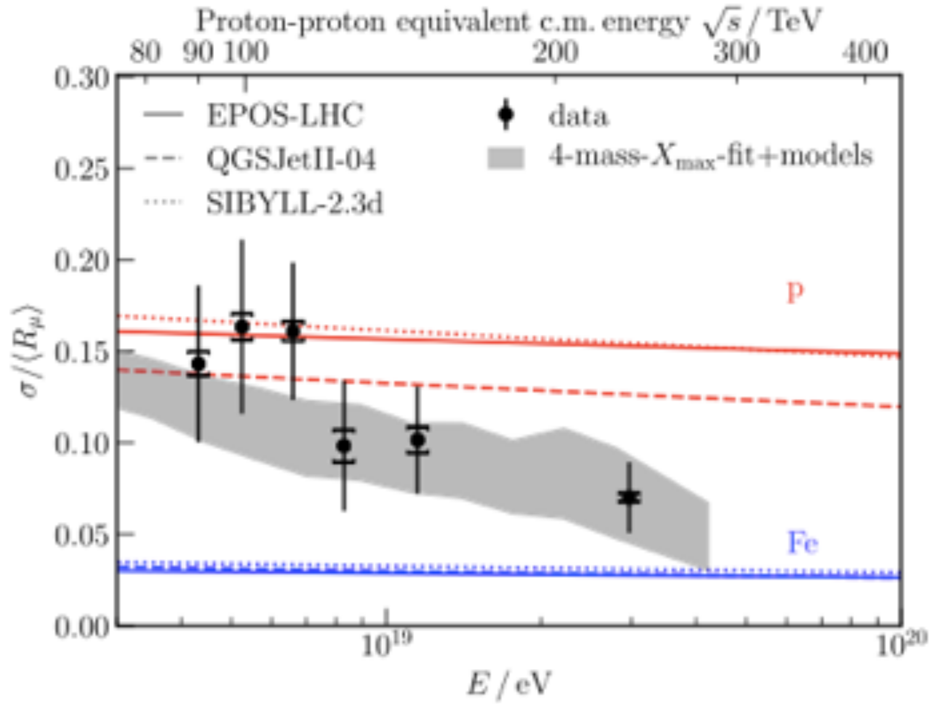


[PRD, 91 (2015) 032003]

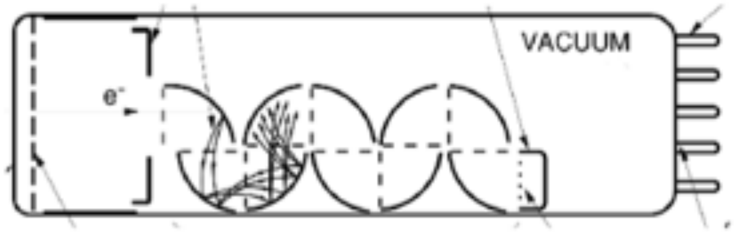
Hybrid events and inclined showers



Discrepancy in number of muons
Relative fluctuations as expected



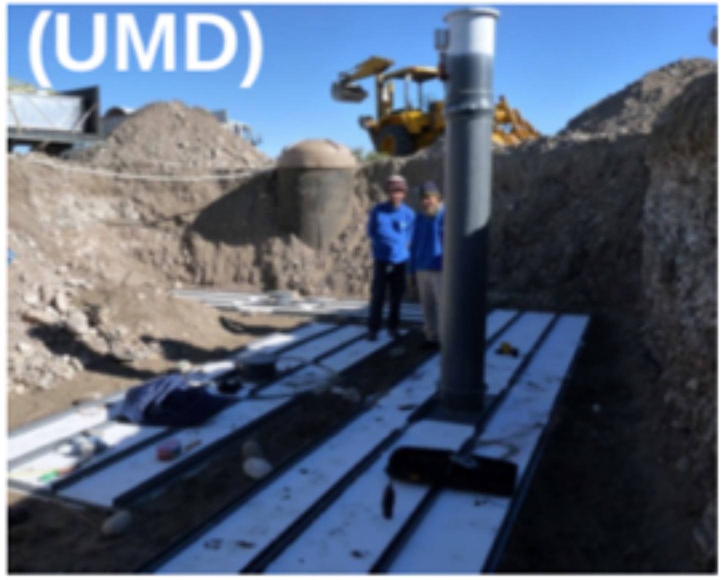
PMT analogy of air shower



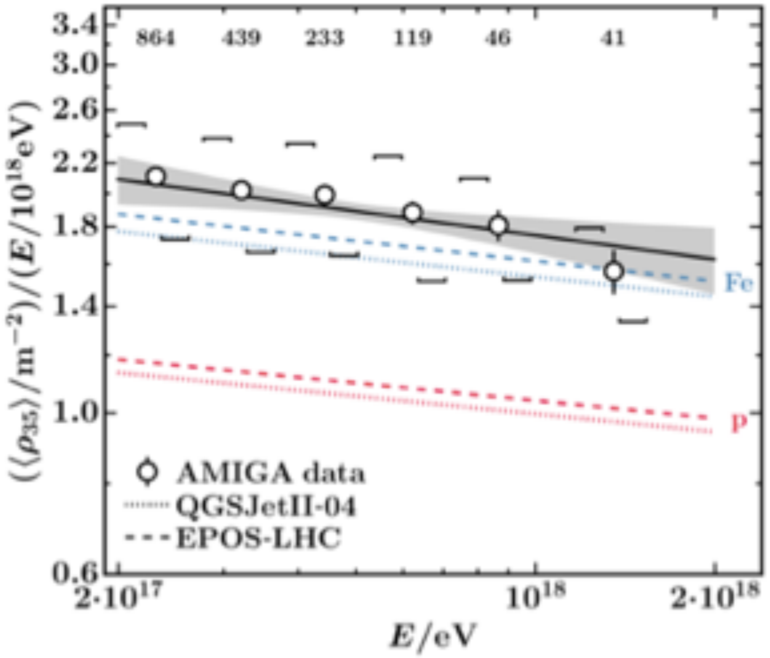
Muon fluctuations driven by first interactions

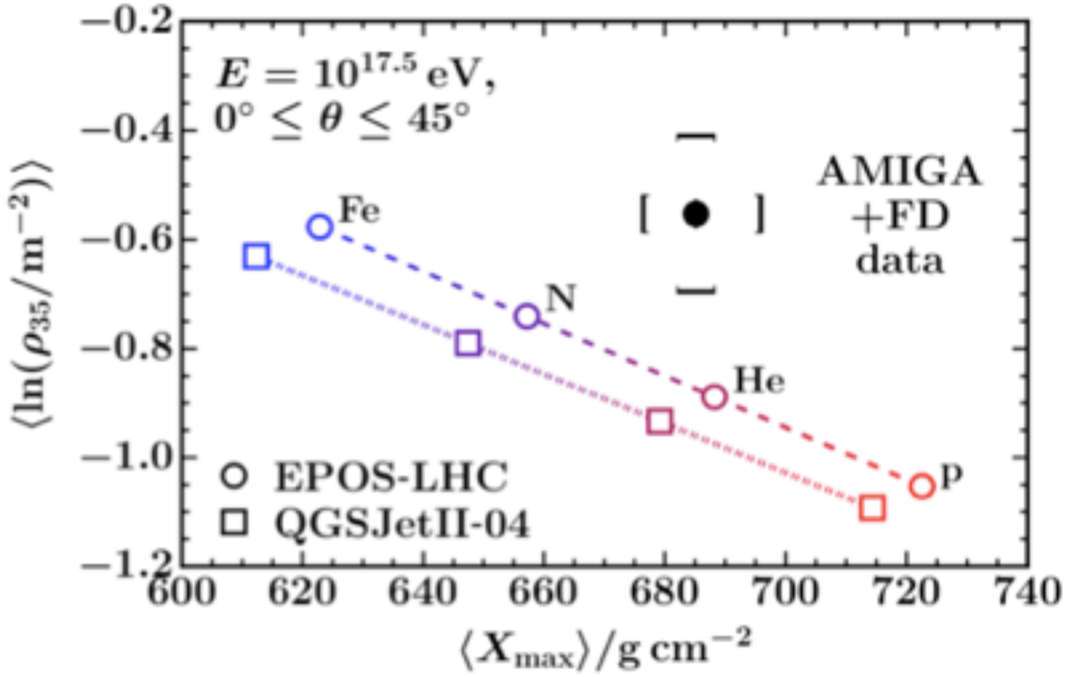
Direct measurement of muons at lower energy

[EPJC, 80 (2020) 751]



Underground muon detectors
(2.3 m soil for shielding)





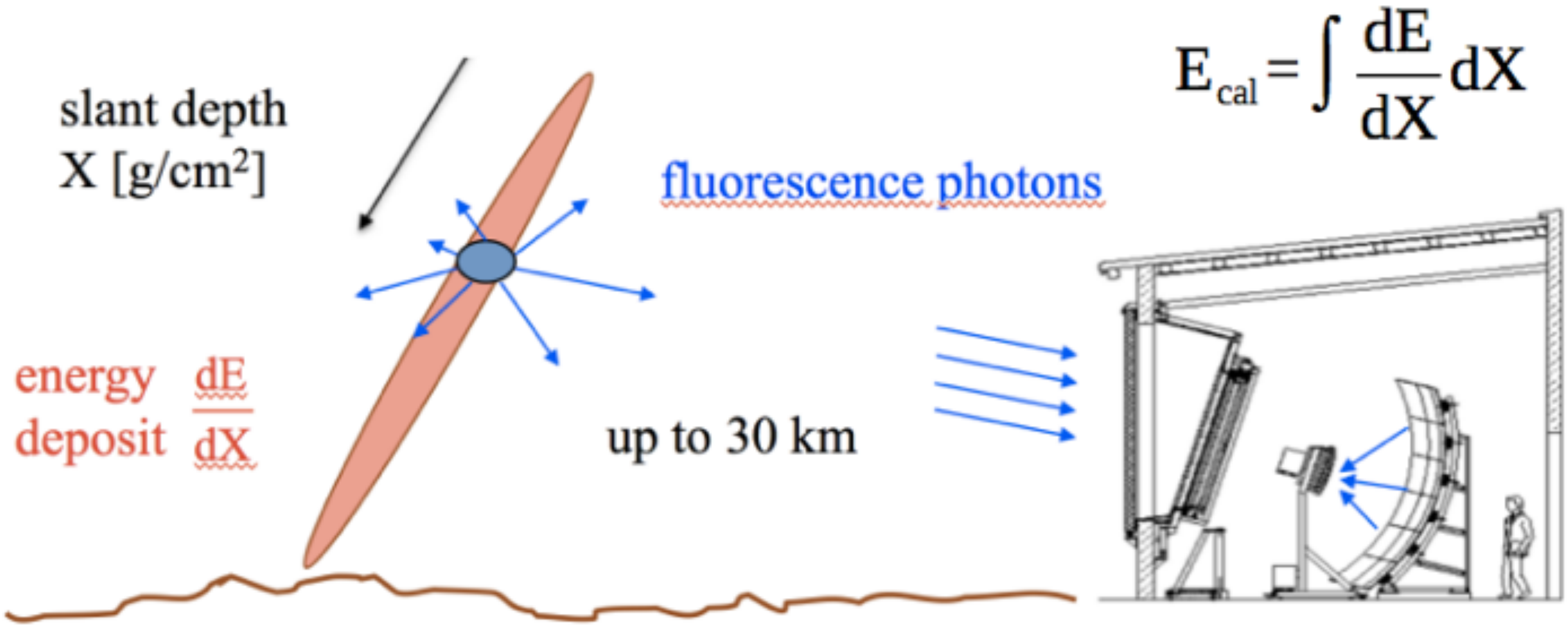
In range 3x10^{17} eV to 2x10^{18} eV simulations don’t reproduce muon densities

38% (53%) increase in <N_{μ}> at 10^{18} eV needed for EPOS-LHC (QGSJetII-04)

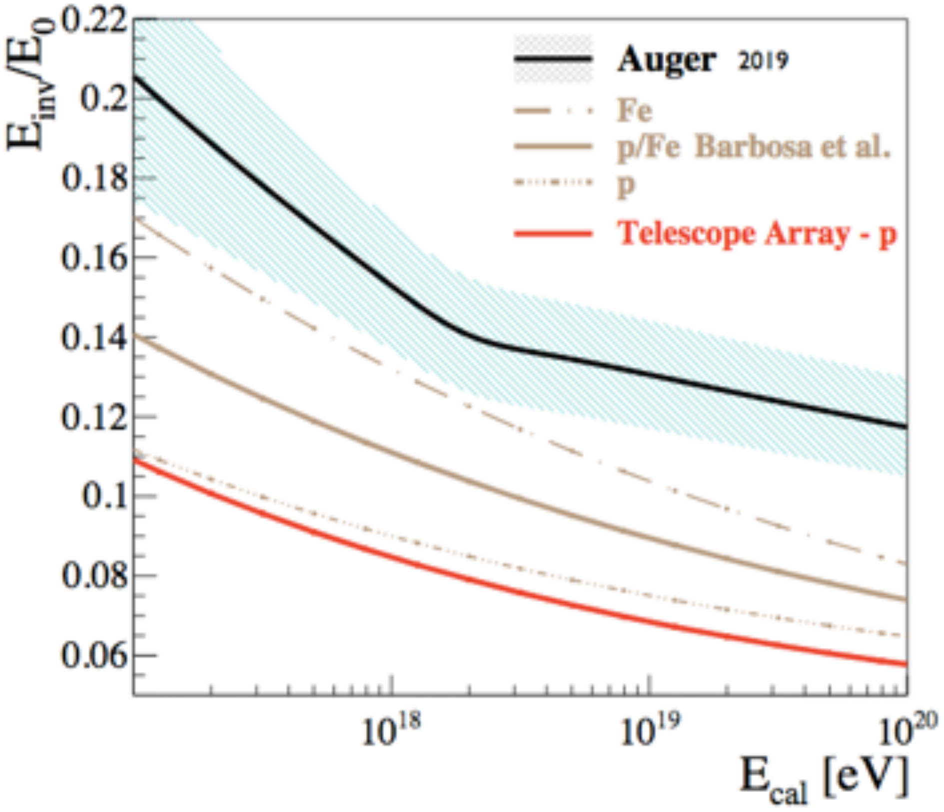
All the rest…

- Upgrade of the Observatory
- Outreach
- Open data
- 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
- …

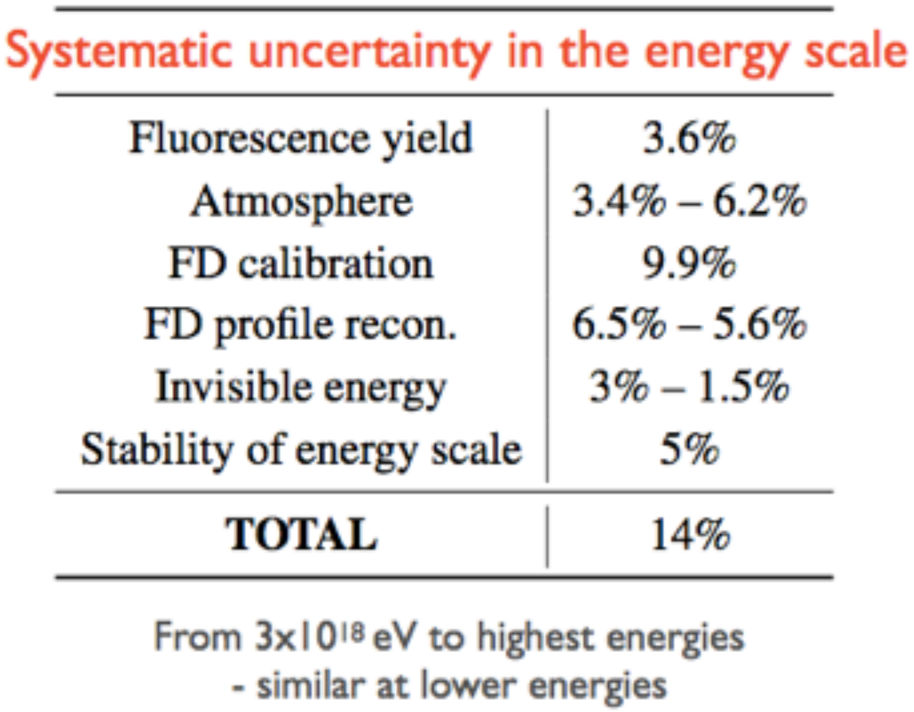
Energy scale



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



[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

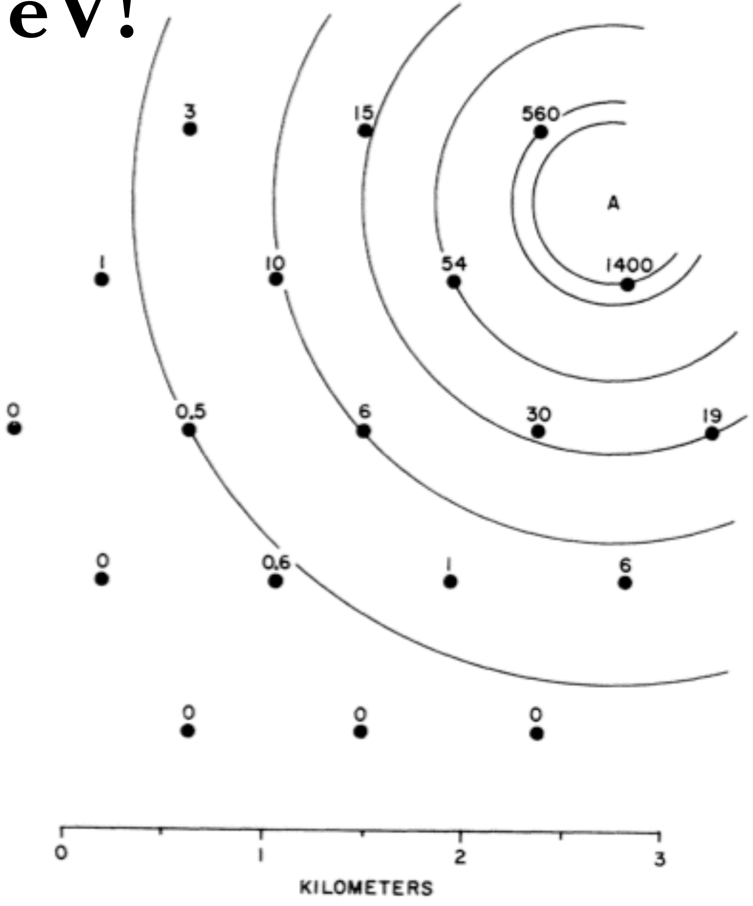
[Dawson, ICRC2019]

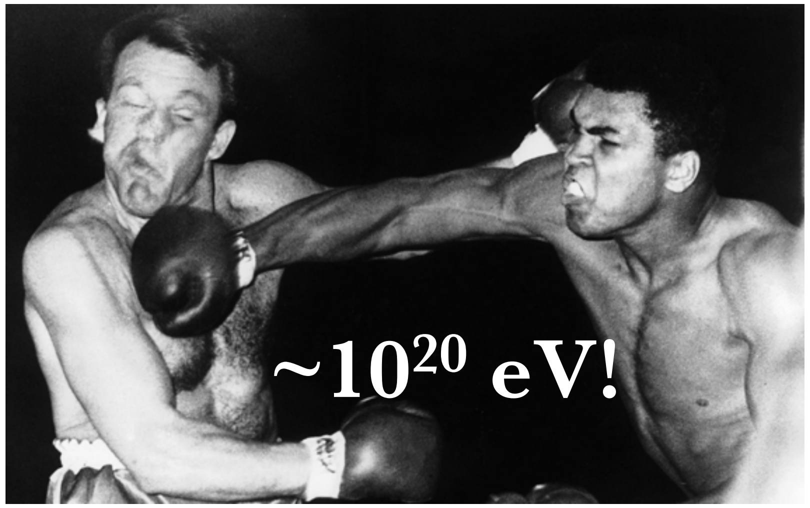
SD: Track-length integral from lateral sampling?

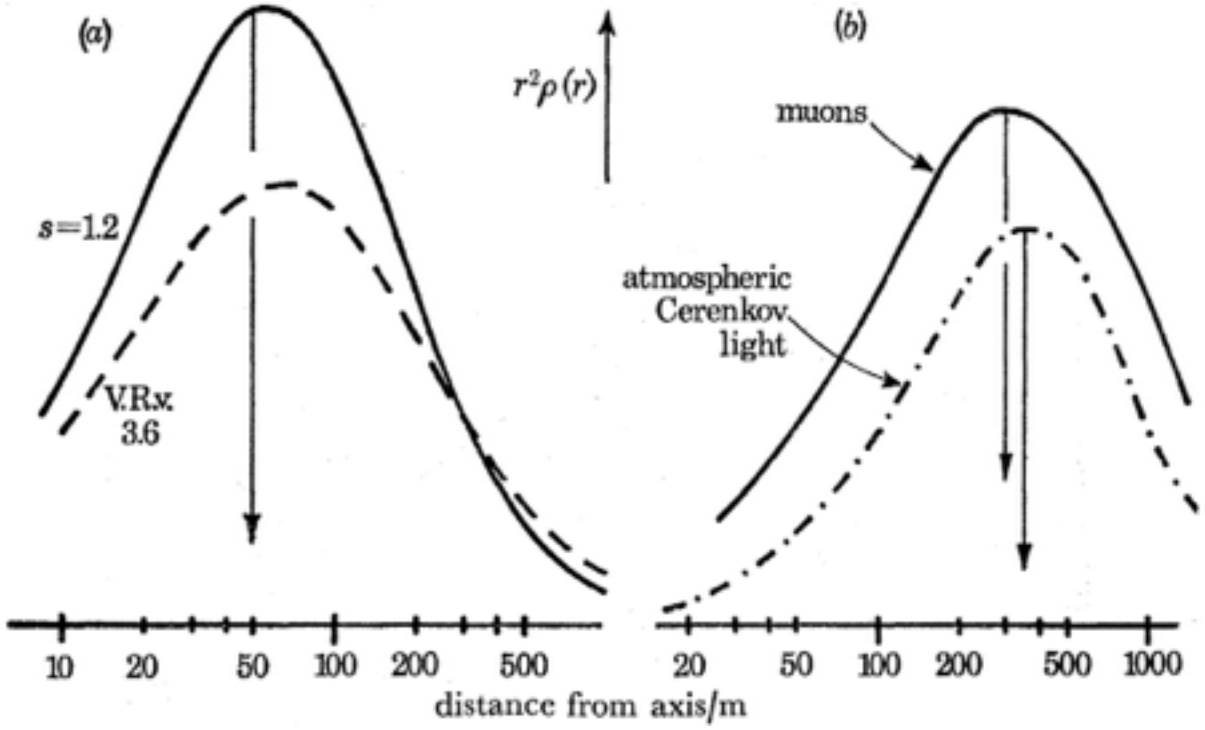
Issue: spacing of detectors > Molière radius

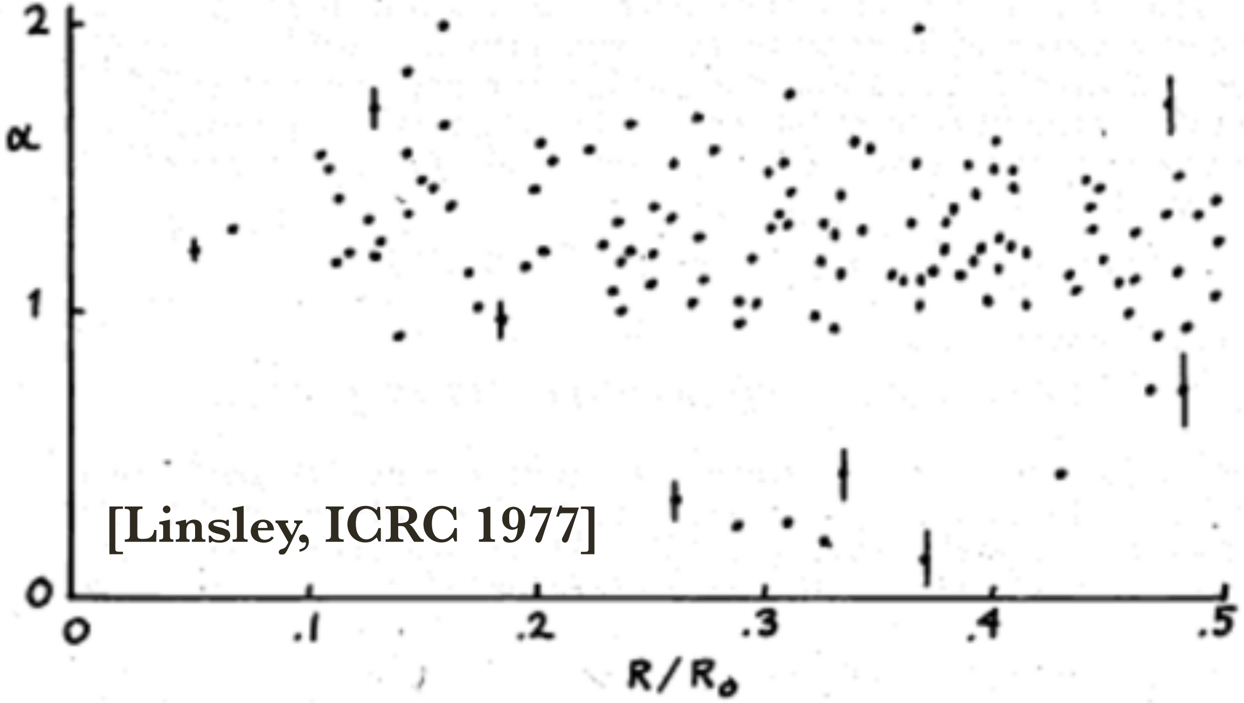
[Linsley, PRL 10:146–148]

~10^{20} eV!



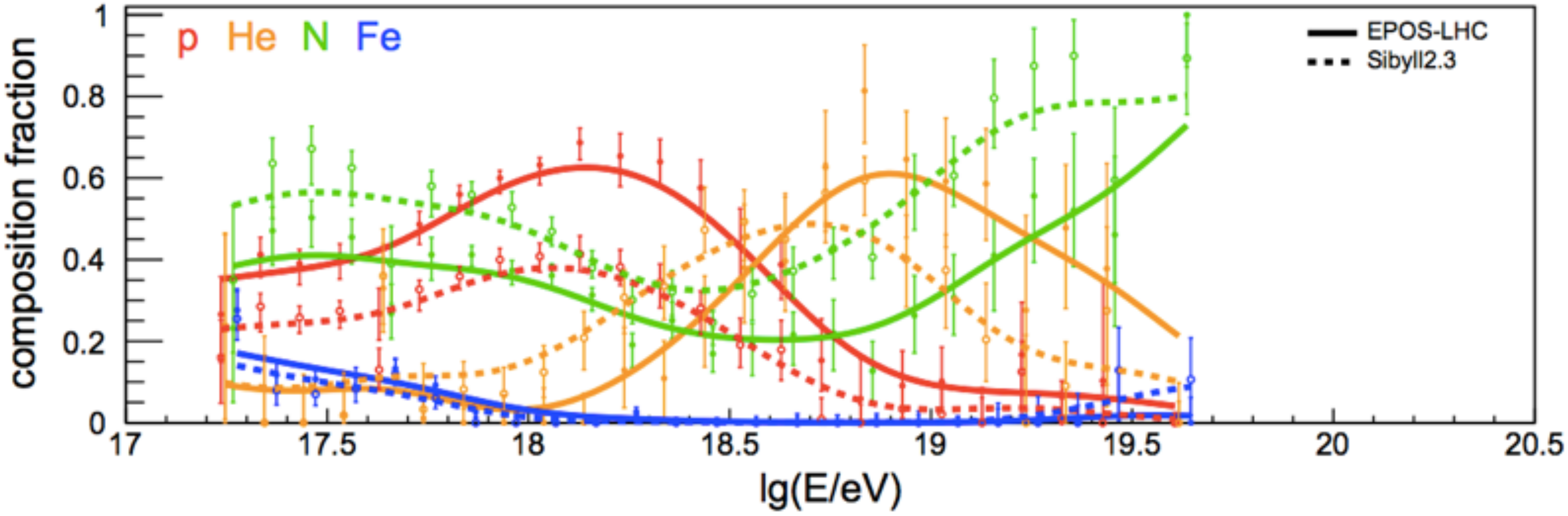


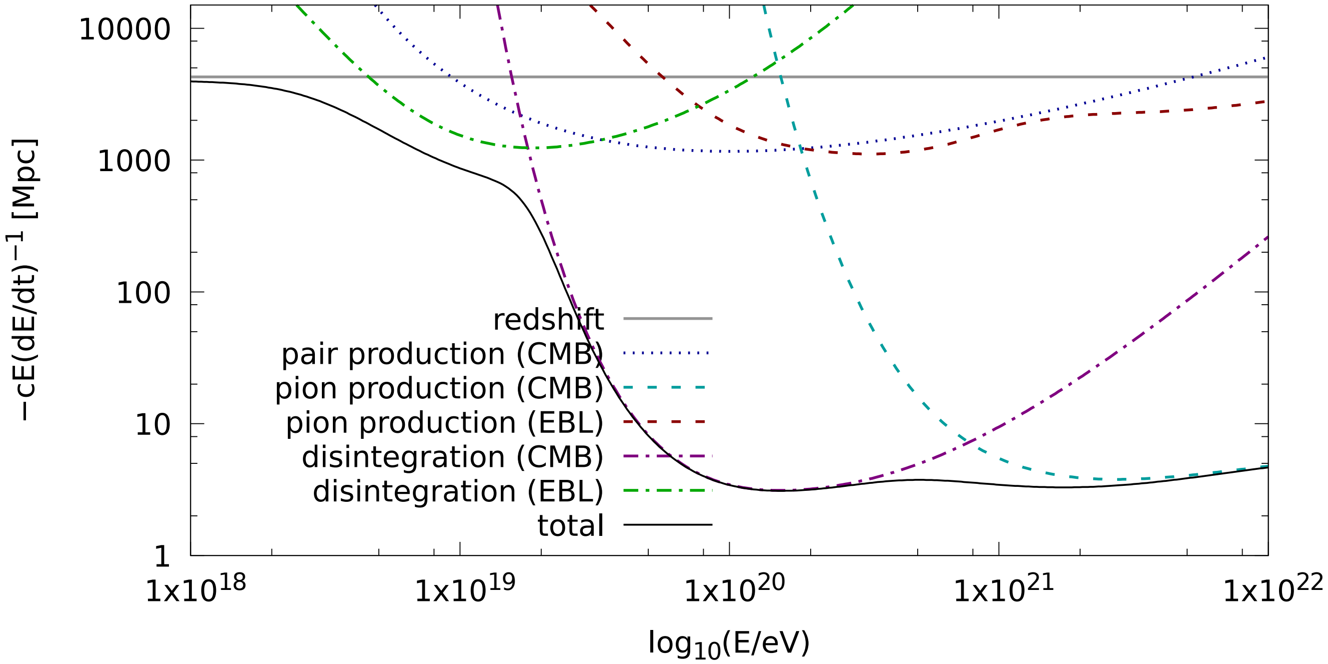


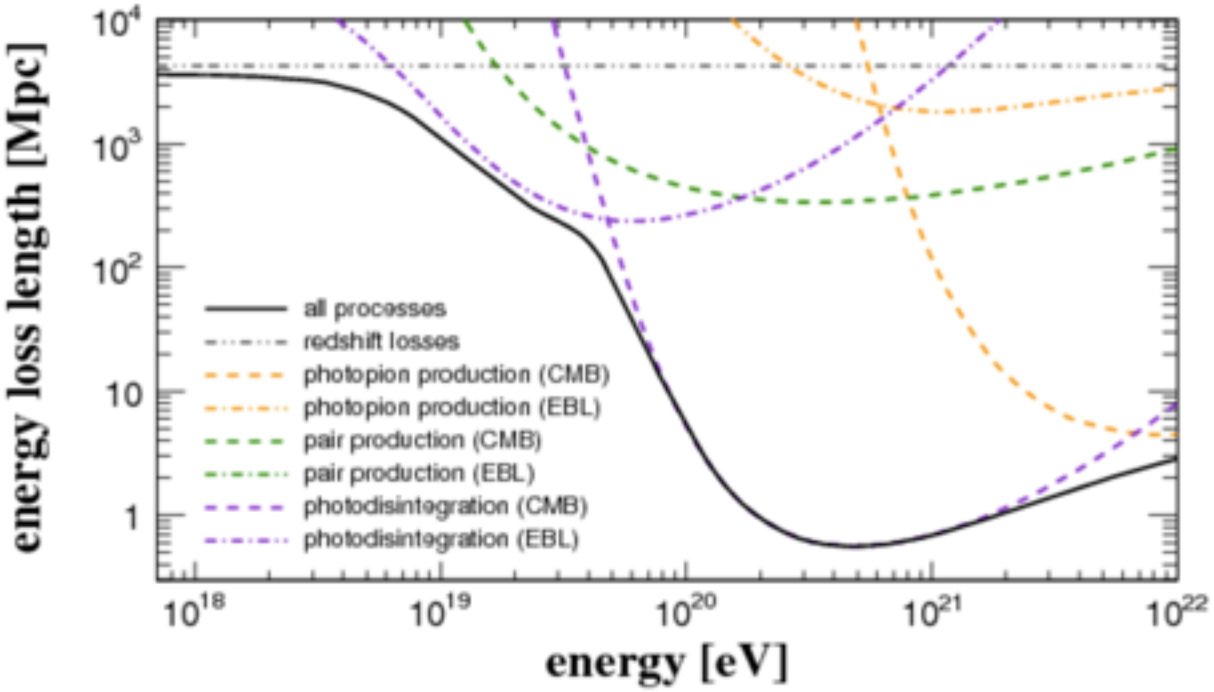


[Linsley, ICRC 1977]

Composition and horizons at UHE







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

☞ Limited horizons @ 30-40 EeV

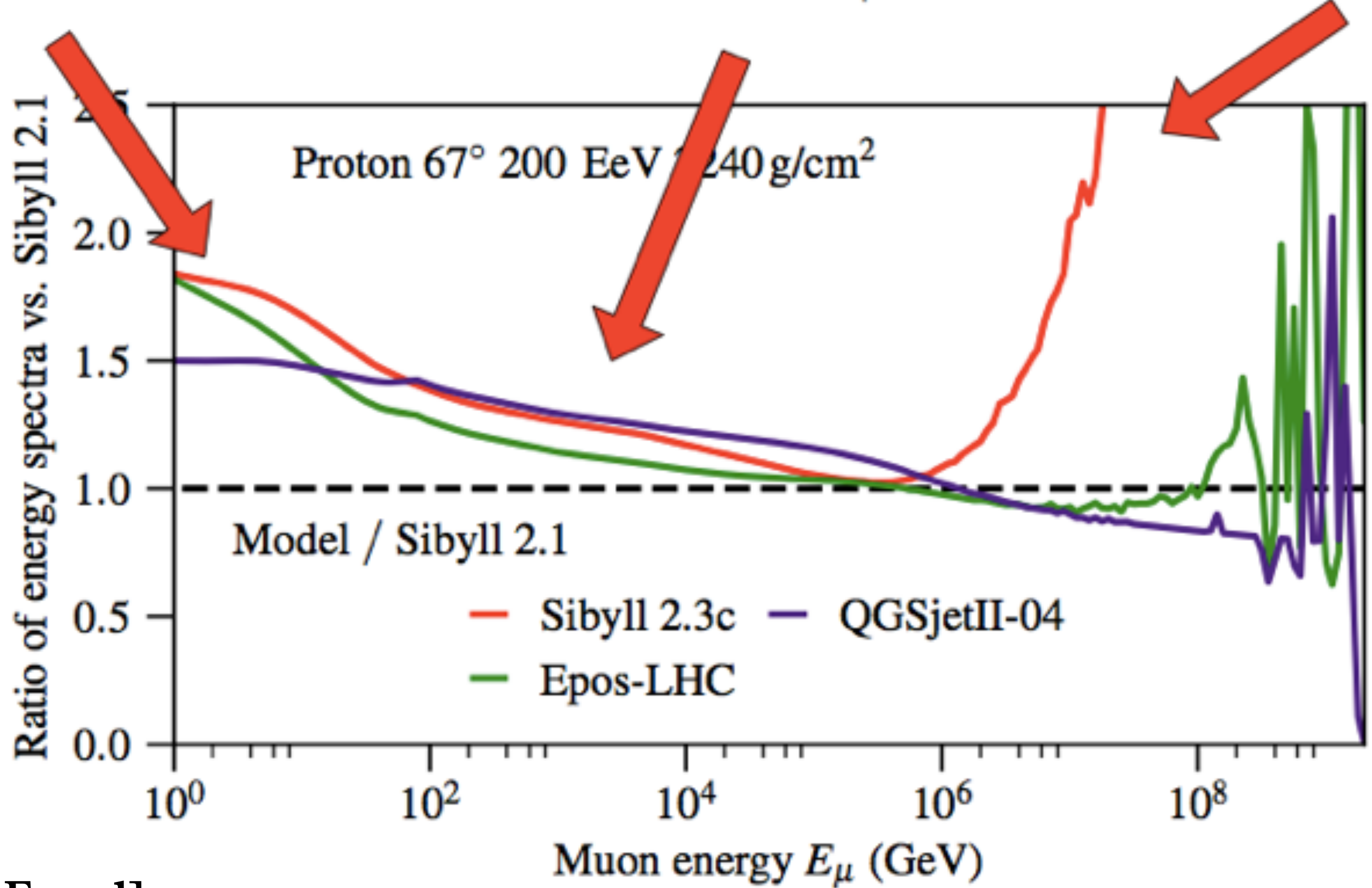
Muon production in hadronic showers

Muon energy spectrum in EAS relative to that of Sibyll 2.1

Low-energy enhancement due to baryon pair production

Rho-0 production

Charm particles (only Sibyll 2.3, and Sibyll 2.3c)



[Courtesy, R. Engel]