Cosmic Rays with the Pierre Auger Observatory: messengers from the Ultra High Energy frontier

May 2018

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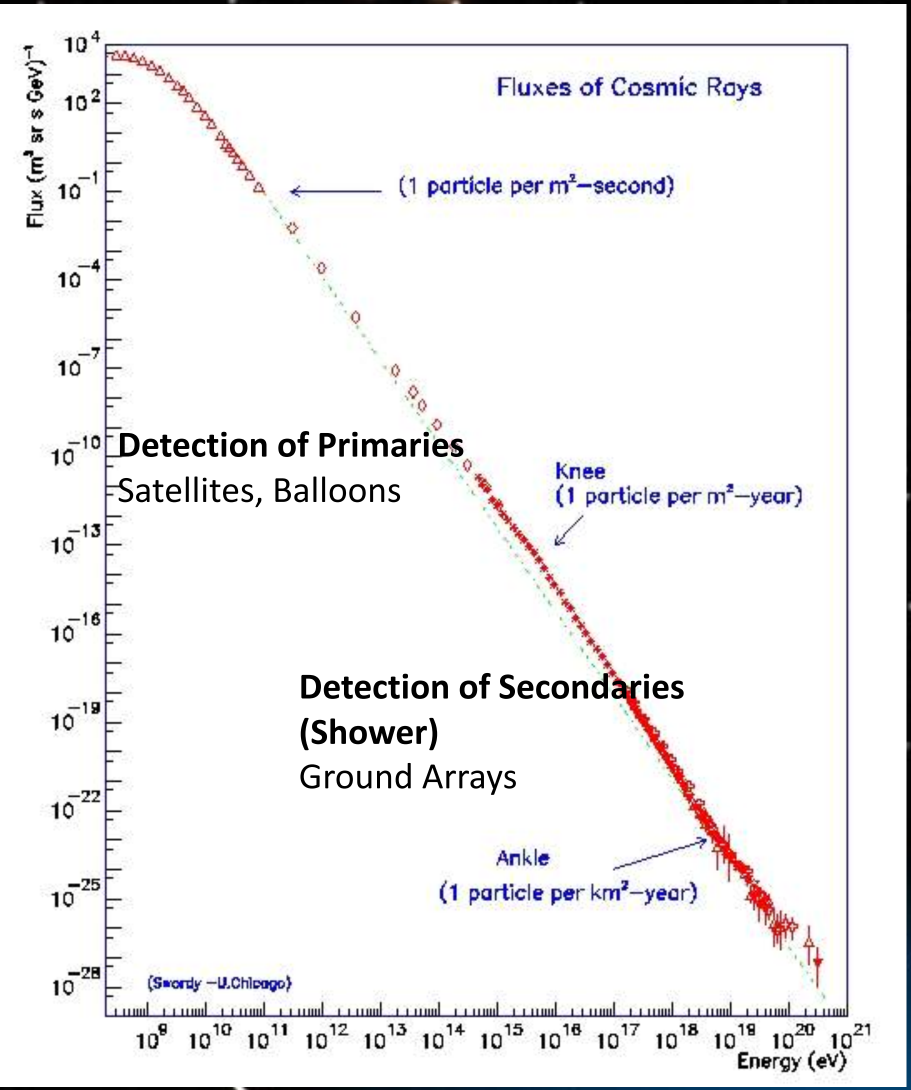
for the Pierre Auger Collaboration

Cosmic Ray Spectrum



14 TeV 100 TeV

- 16 particles above log(E/eV)=18.6 arrive at Earth each second
- The Pierre Auger Observatory collects around 3000 / year.

Accelerator's comparison

1.5 eV

10 000.0 eV

6 500 000 000 000.0 eV

300 000 000 000 000 000 000.0 eV

Gigantic energies

The energy of 10 g (rest mass) of the highest energy cosmic rays is the equivalent of 1000 times the energy of all world's fossil fuel reserves.

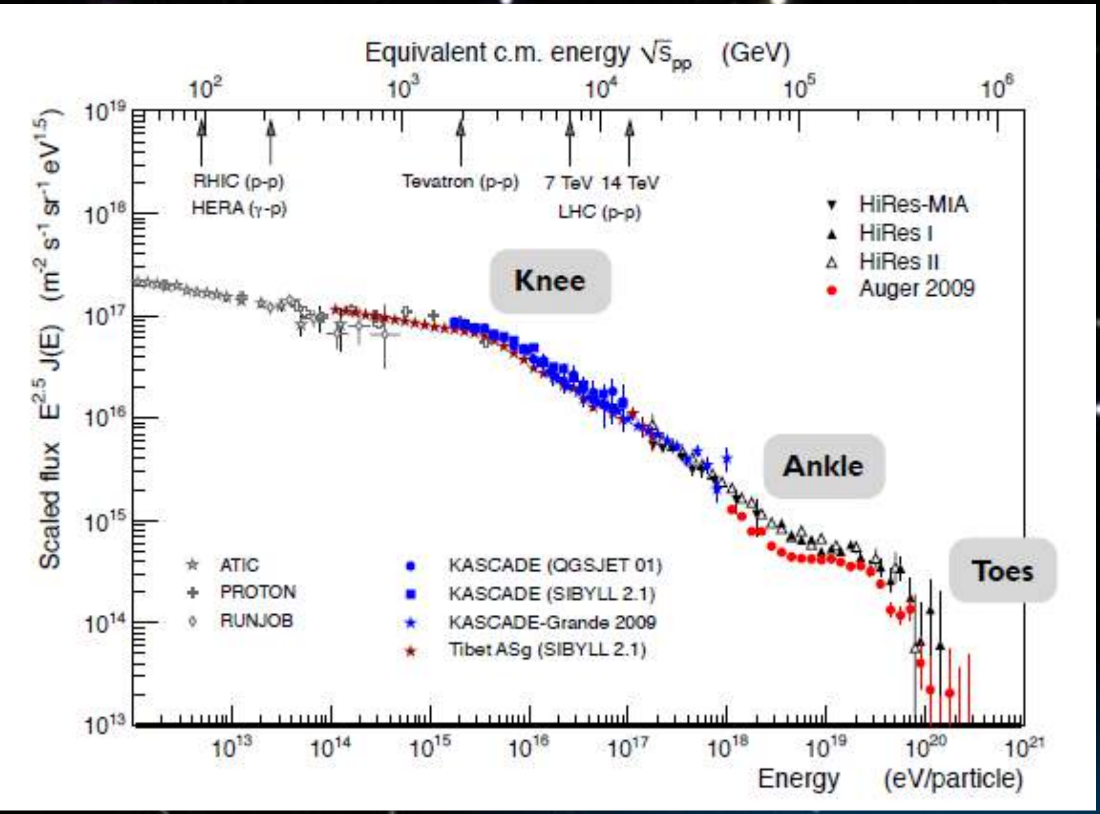
$$10\ g \cdot 1\frac{mol}{g} \cdot N_A \cdot 50\, J = 3 \cdot 10^{26}\, J$$

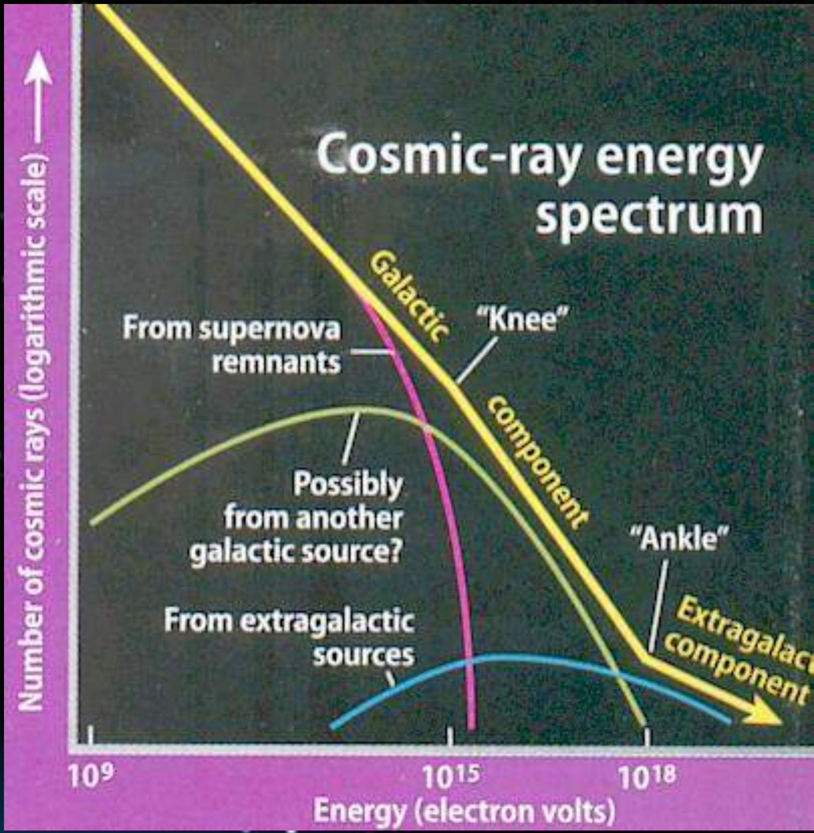
10^{18}	Exa- (EJ)	1.4×10^{18} J	Yearly electricity consumption of South Korea as of 2009[146][158]
10^{19}		1.4×10^{19} J	Yearly electricity consumption in the U.S. as of 2009[146][159]
		1.4×10^{19}J	Yearly electricity production in the U.S. as of 2009[160][161]
		5×10^{19} J	Energy released in 1-day by an average hurricane in producing rain (400 times greater than the wind energy)[144]
		6.4×10^{19} J	Yearly electricity consumption of the world as of 2008[162][163]
		6.8×10^{19} J	Yearly electricity generation of the world as of 2008[162][164]
10^{20}		5×10^{20} J	Total world annual energy consumption in 2010[165][166]
		8×10^{20} J	Estimated global uranium resources for generating electricity 2005[167][168][169][170]
10^{21}	Zetta- (ZJ)	6.9×10^{21} J	Estimated energy contained in the world's natural gas reserves as of 2010[165][171]
		7.9×10^{21} J	Estimated energy contained in the world's petroleum reserves as of 2010[165][172]
10^{22}		1.5×10^{22}J	Total energy from the Sun that strikes the face of the Earth each day[152][173]
		2.4×10^{22} J	Estimated energy contained in the world's coal reserves as of 2010[165][174]
		2.9×10^{22} J	Identified global uranium-238 resources using fast reactor technology[167]
		3.9×10^{22} J	Estimated energy contained in the world's fossil fuel reserves as of 2010[165][175]
		4×10^{22} J	Estimated total energy released by the magnitude 9.1–9.3 2004 Indian Ocean earthquake[176]
10^{23}		2.2×10^{23} J	Total global uranium-238 resources using fast reactor technology[167]
		5×10^{23} J	Approximate energy released in the formation of the Chicxulub Crater in the Yucatán Peninsula[177]
10^{24}	Yotta- (YJ)	5.5×10^{24} J	Total energy from the Sun that strikes the face of the Earth each year[152][178]
10^{25}		6×10^{25} J	Energy released by a typical solar flare
10^{26}		1.3×10^{26} J	Conservative estimate of the energy released by the impact that created the Caloris basin on Mercury[citation needed]
		3.8×10^{26} J	Total energy output of the Sun each second[179]
10^{27}			
10^{28}		3.8×10^{28} J	Kinetic energy of the Moon in its orbit around the Earth (counting only its velocity relative to the Earth)[180][181]
10^{29}		2.1×10^{29} J	Rotational energy of the Earth[182][183][184]
10^{30}		1.8×10^{30} J	Gravitational binding energy of Mercury
10^{31}		3.3×10^{31} J	Total energy output of the Sun each day[179][185]
10^{32}		2×10^{32} J	Gravitational binding energy of the Earth[186]

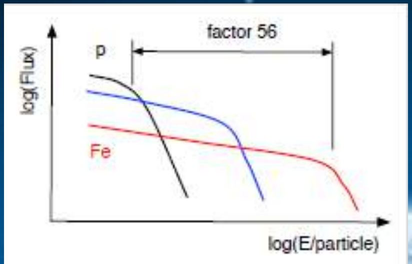
The questions:

- What are the UHECR?
  - Light nuclei? Heavy nuclei?
    - **Do we understand their interactions at all at those energies???**
  - Are there neutrinos, photons, or neutrons pointing back to interesting places?
  - Are there exotic UHECR? Monopoles? Miniblack holes?
- Where are UHECR produced?
  - Do they come from the decay of some cosmologic relic, super heavy particles?
  - Or are they accelerated in violent places?
- If so, where are those places? We should see them, and we don't!!!!
  - We know that those places must be nearby (<100MPc) because of the GZK effect.

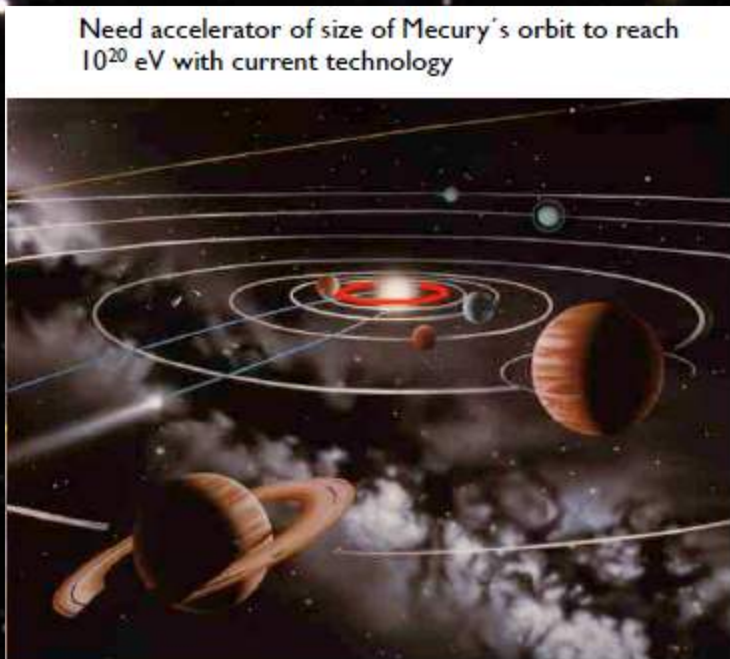
Structure -> hints about origin

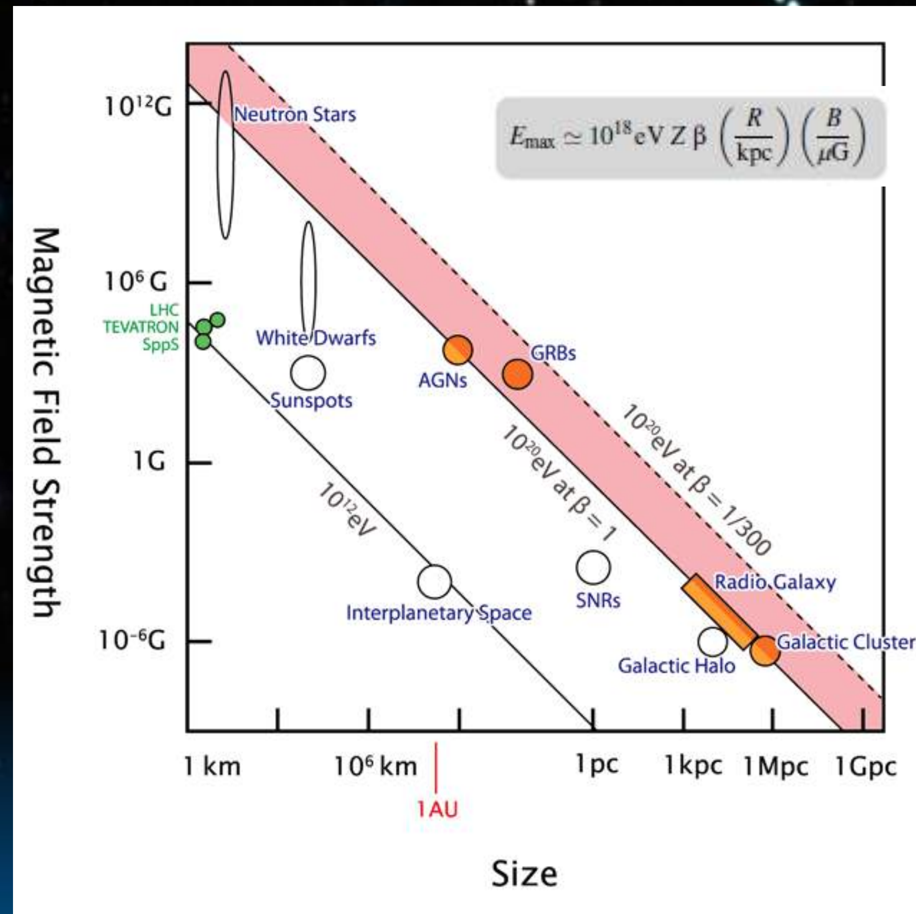






Super-Powerful Accelerators in Nature 1E20eV



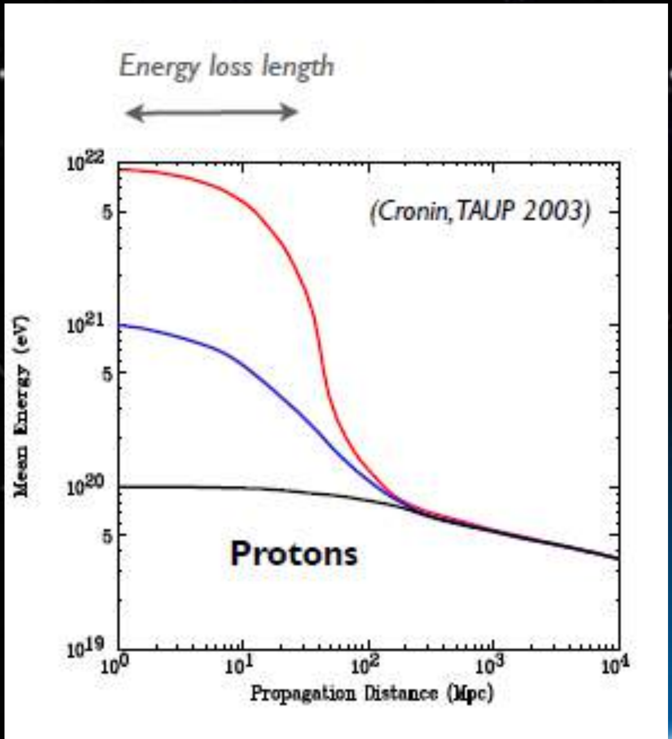


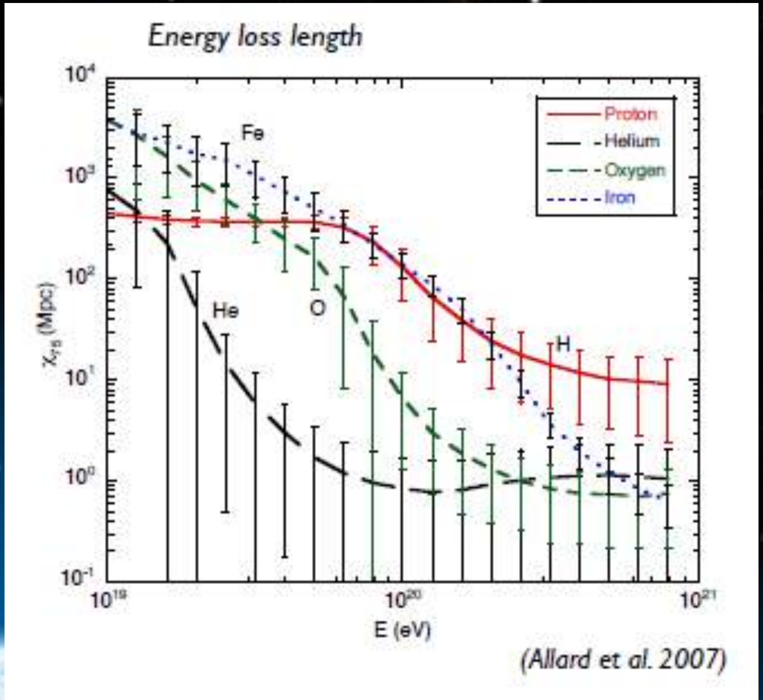
Few astrophysical objects comply with the size and B field required for containment of the CR trajectories at those energies

Interactions with the CMB
Does the spectrum terminate?

$$\gamma_{\rm CMB} + p \rightarrow \Delta^+ \rightarrow p + \pi^0, \quad \rightarrow \gamma + \gamma$$

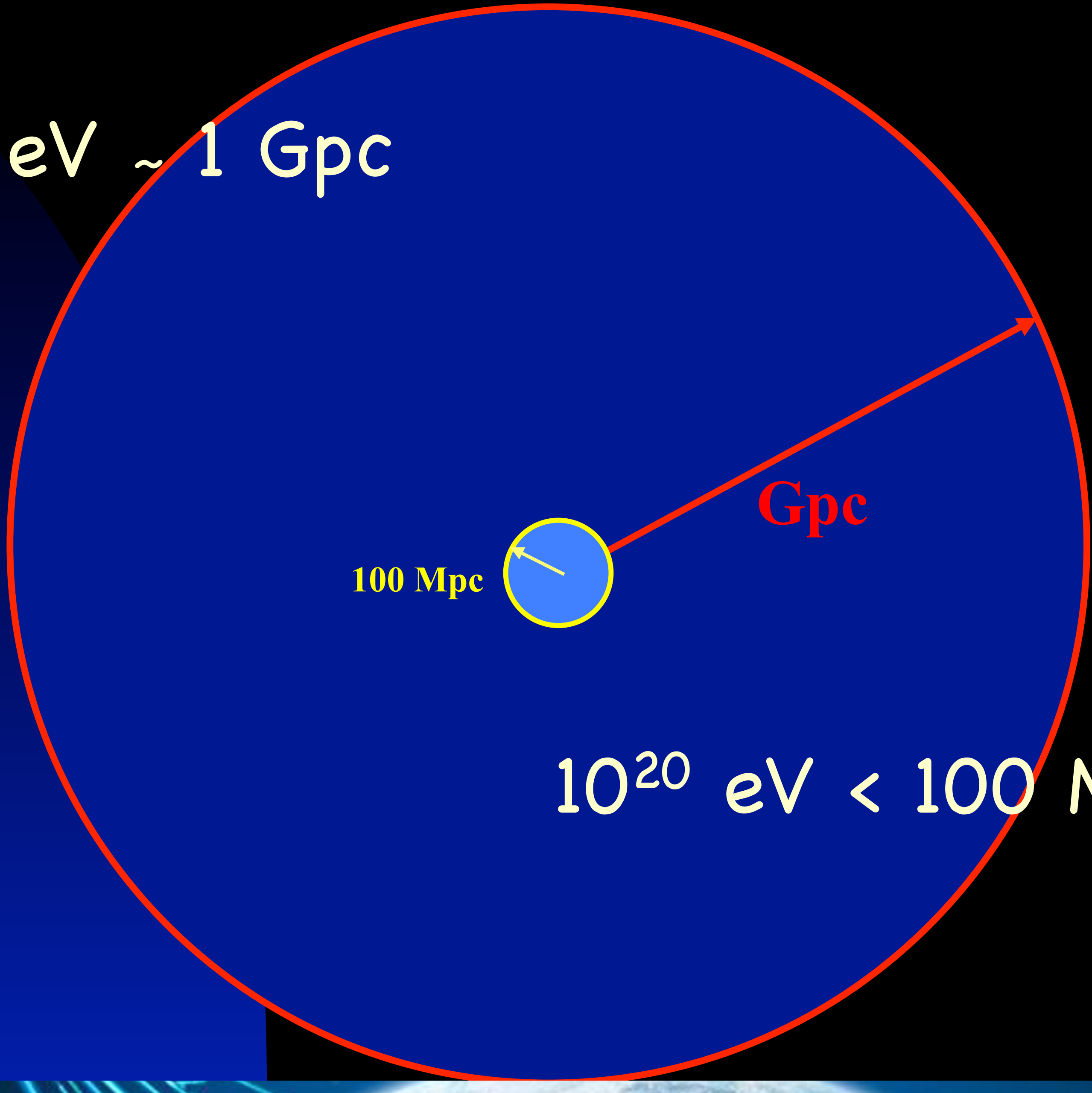
$$\gamma_{\rm CMB} + p \rightarrow \Delta^+ \rightarrow n + \pi^+. \quad \rightarrow \mu^+ + \nu_\mu$$





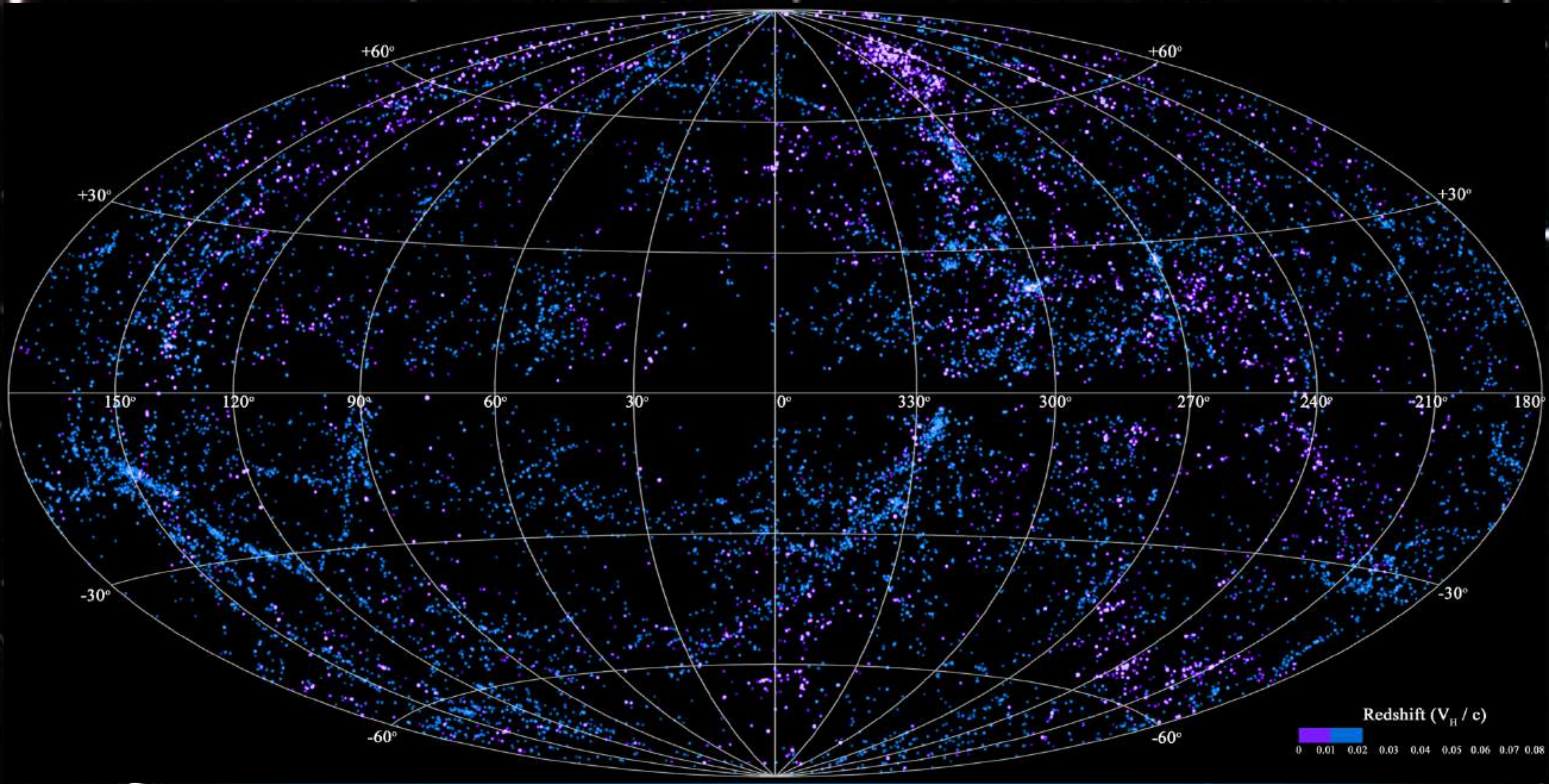
Horizons:

10^{19} eV ~ 1 Gpc

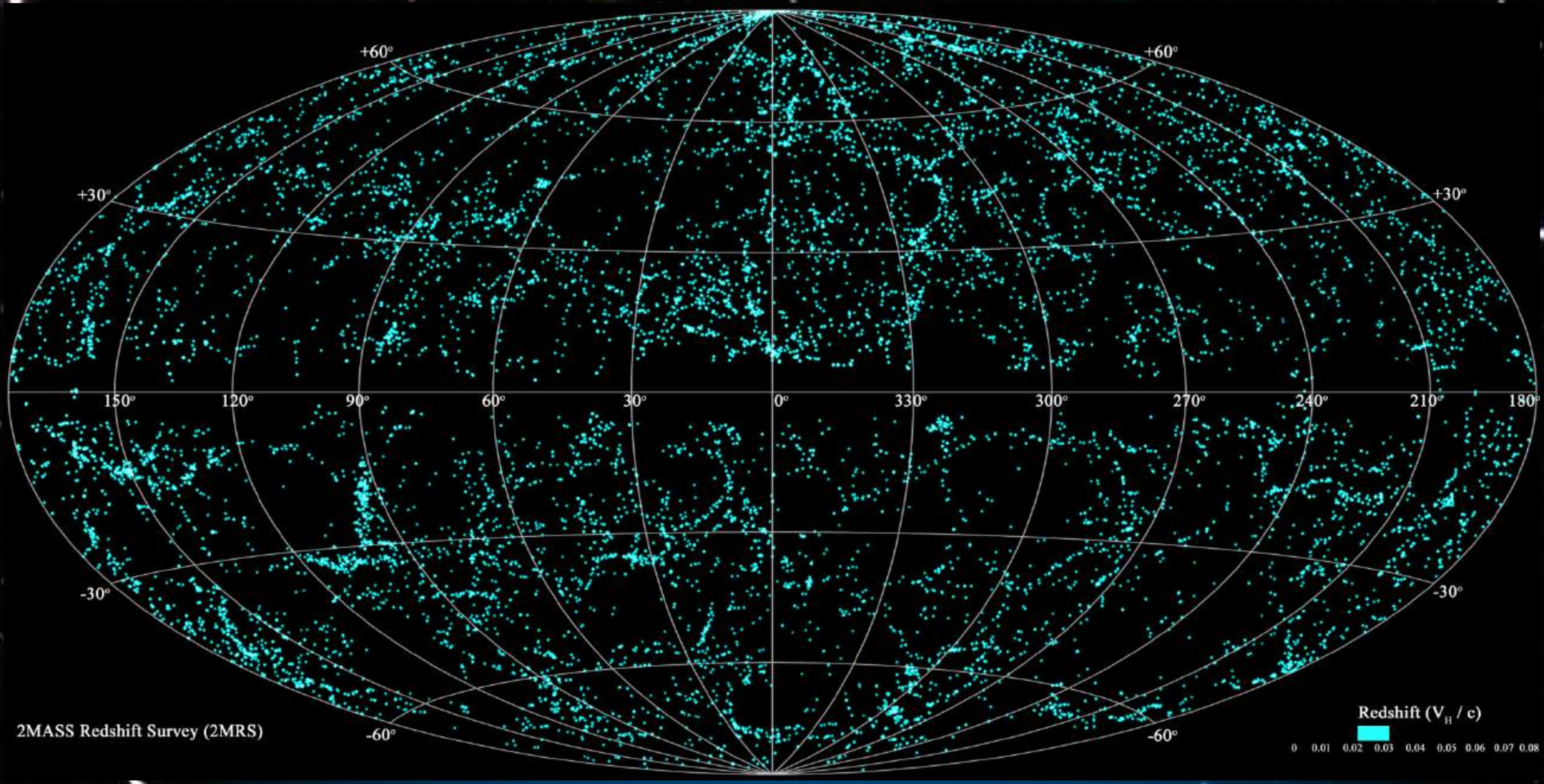


10^{20} eV < 100 Mpc

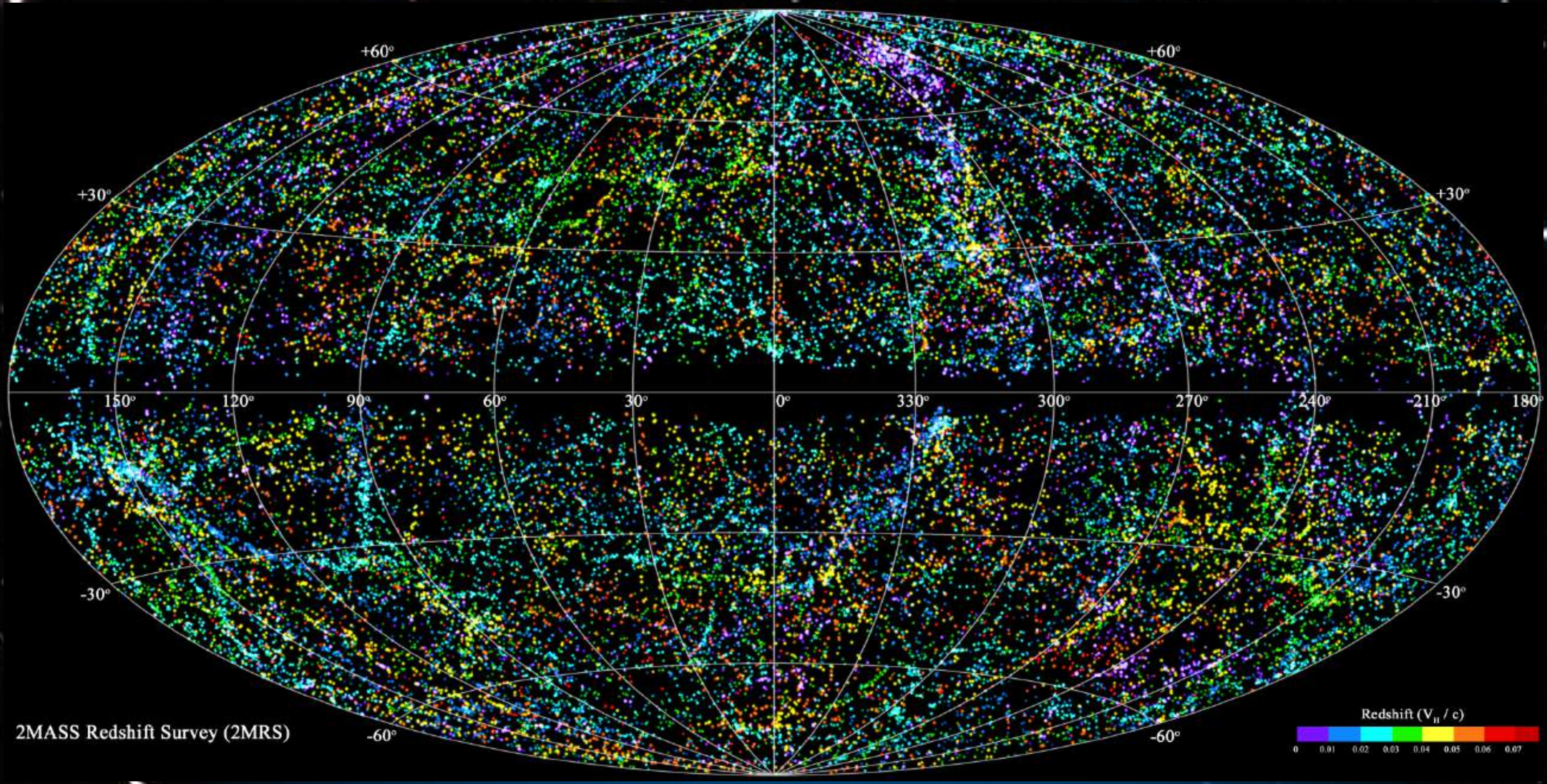
The GZK sphere: 100Mpc matter distribution is anisotropic



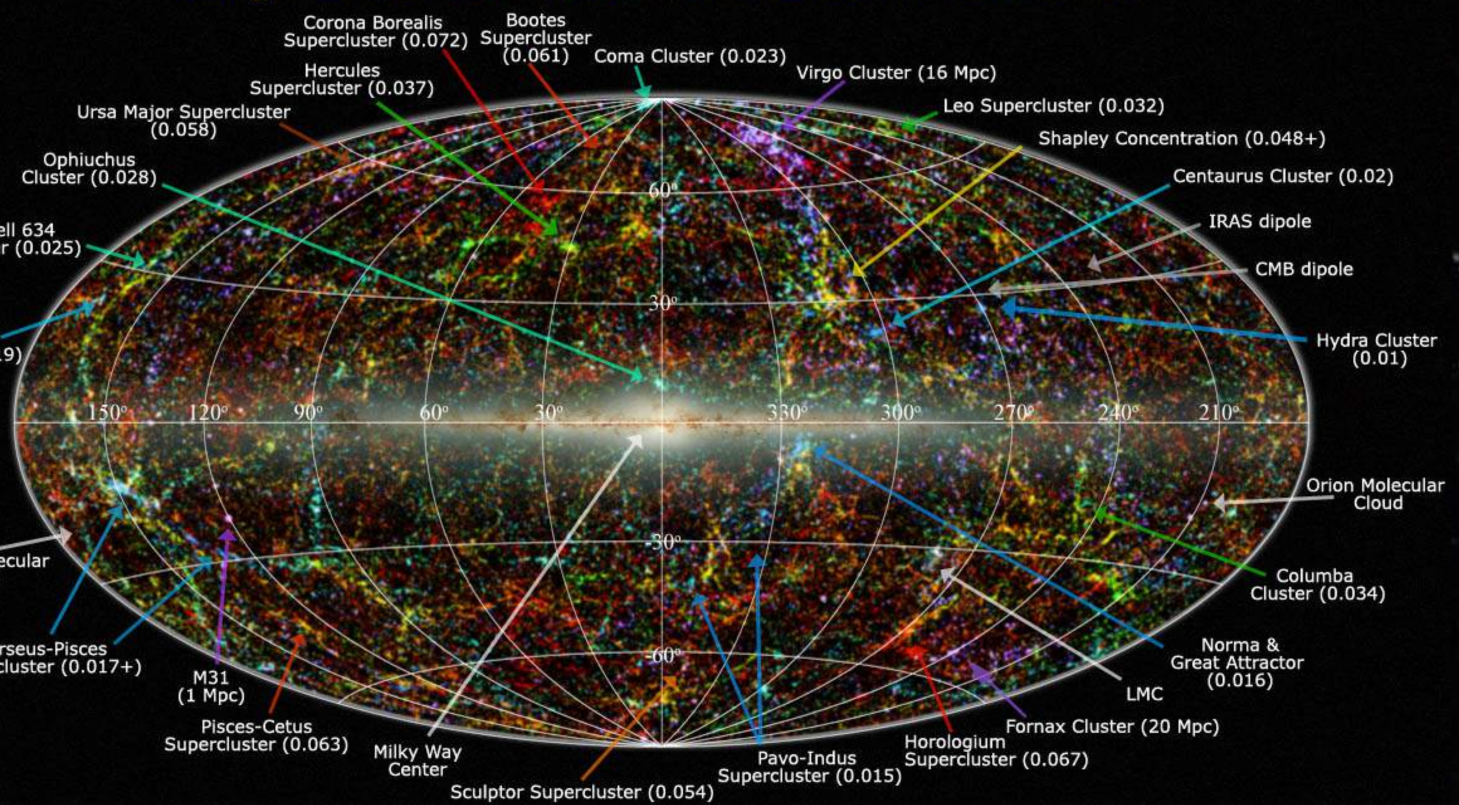
The GZK sphere: 100Mpc matter distribution is anisotropic



As the volume increases, we approach isotropy



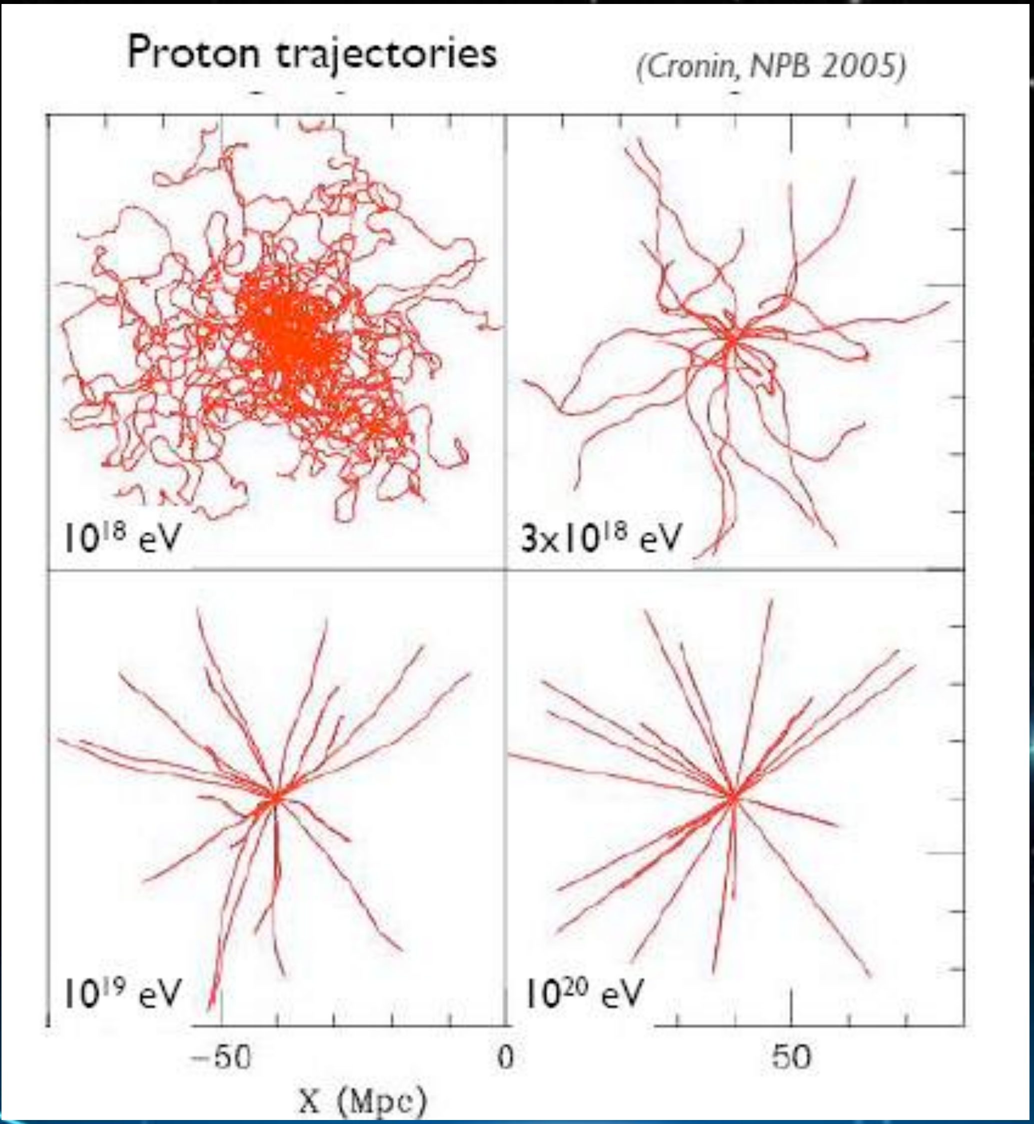
Large Scale Structure in the Local Universe



Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004); familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift). Graphic created by T. Jarrett (IPAC/Caltech)

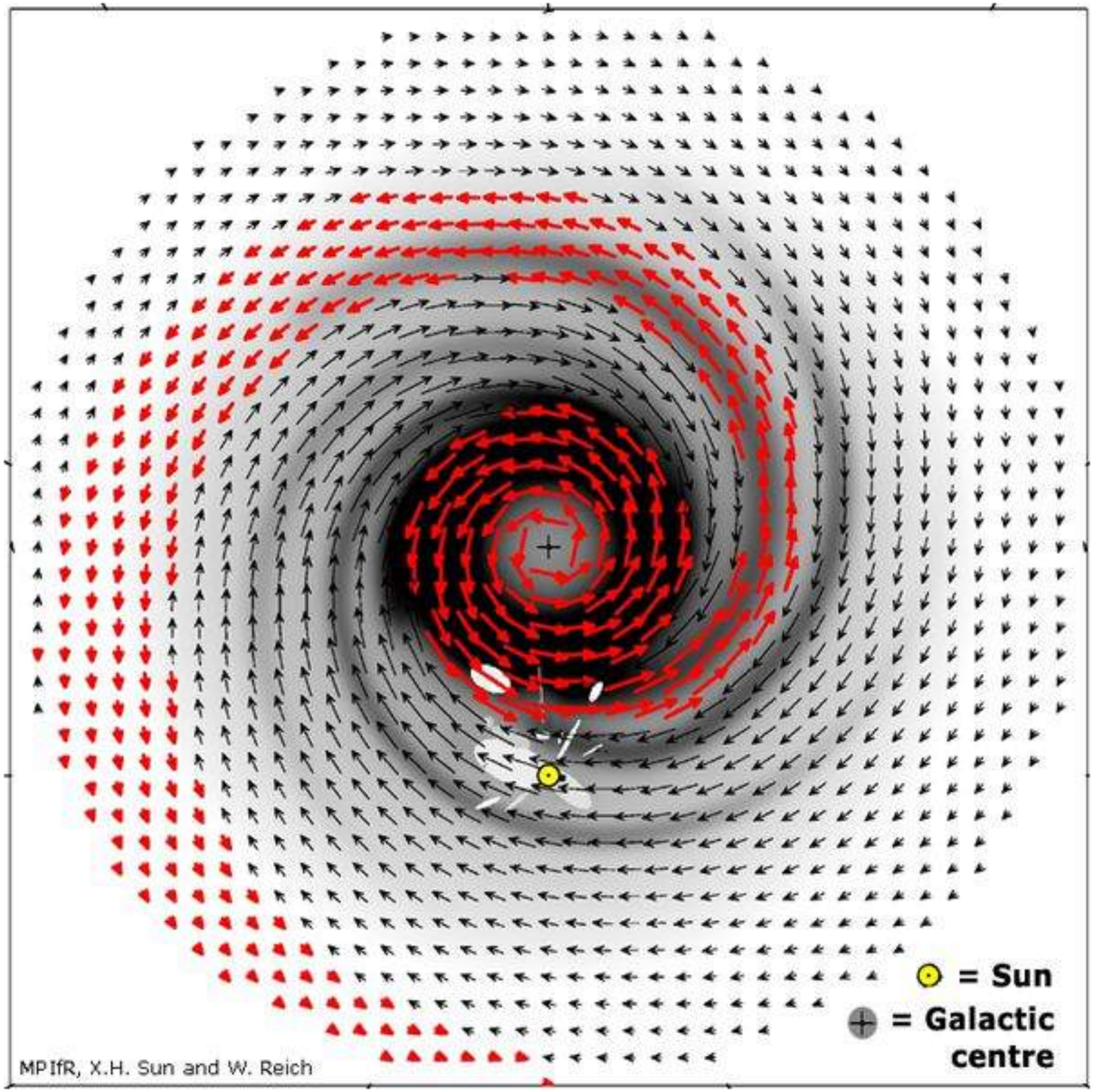
$$\gamma_{CMB} + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+}.$$

B field effects



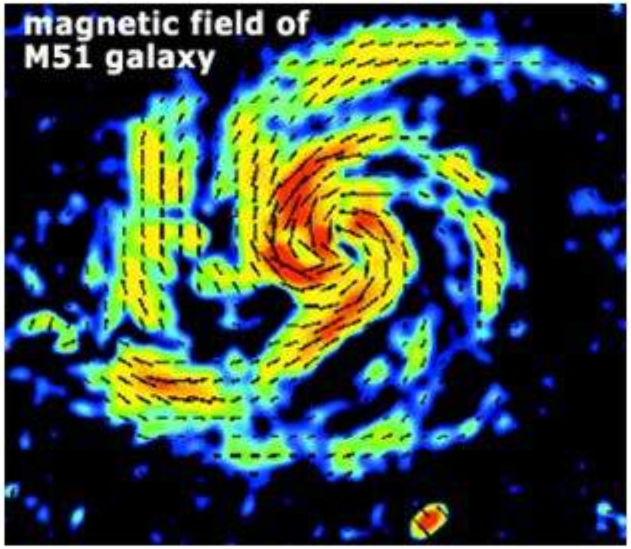
Simple model for extragalactic B. B=1 nG, Lcoh=1 MPc

The magnetic fields of our galaxy, the Milky Way



The main magnetic field structure lies *in the plane* of the disc and follows the spiral arms.

- The red arrows are in the opposite direction to the black ones – i.e. the magnetic field is reversed.
- There is also a toroidal and a poloidal magnetic field (not shown)

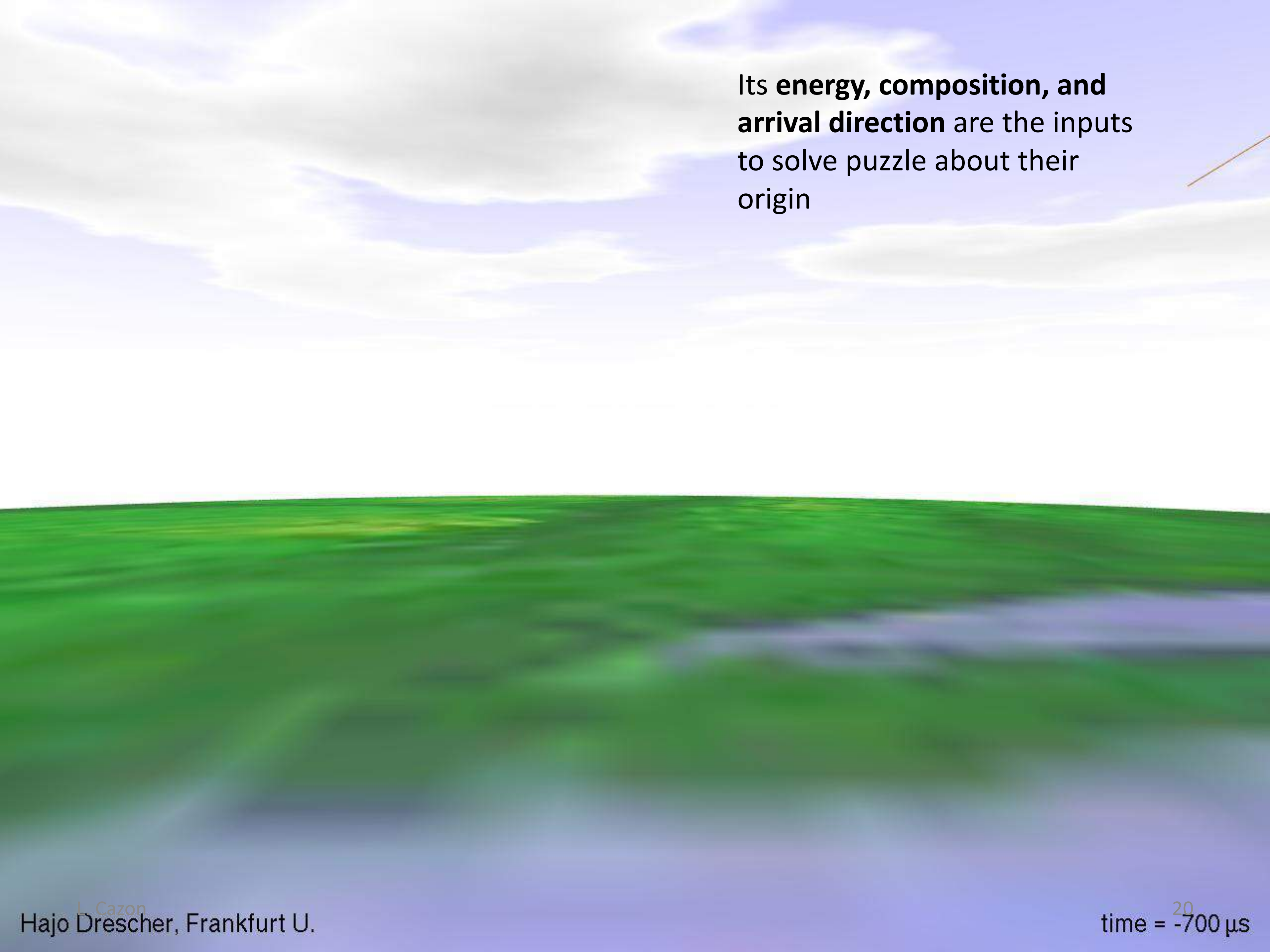


An Air Shower

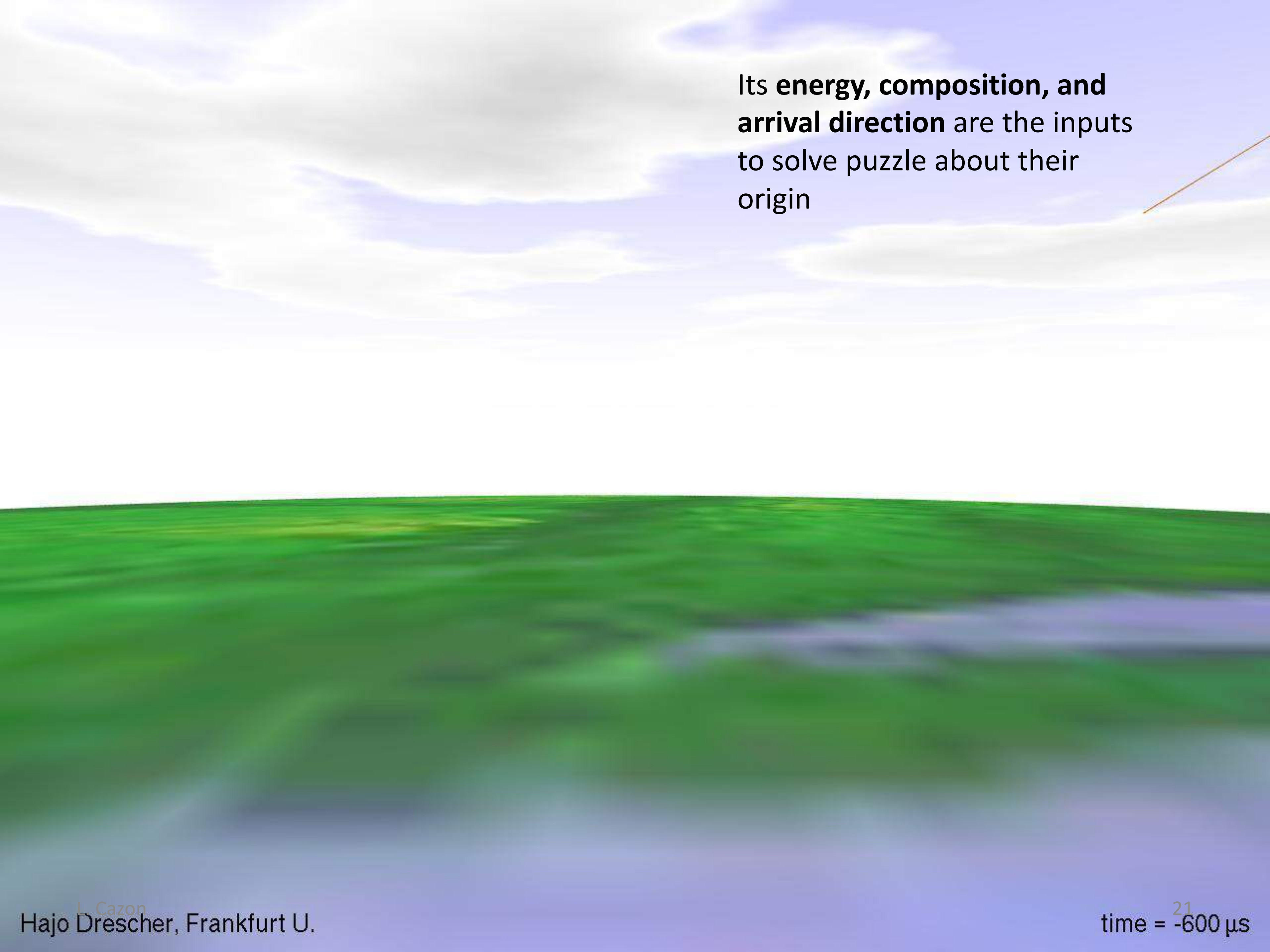
An Air Shower

An Air Shower

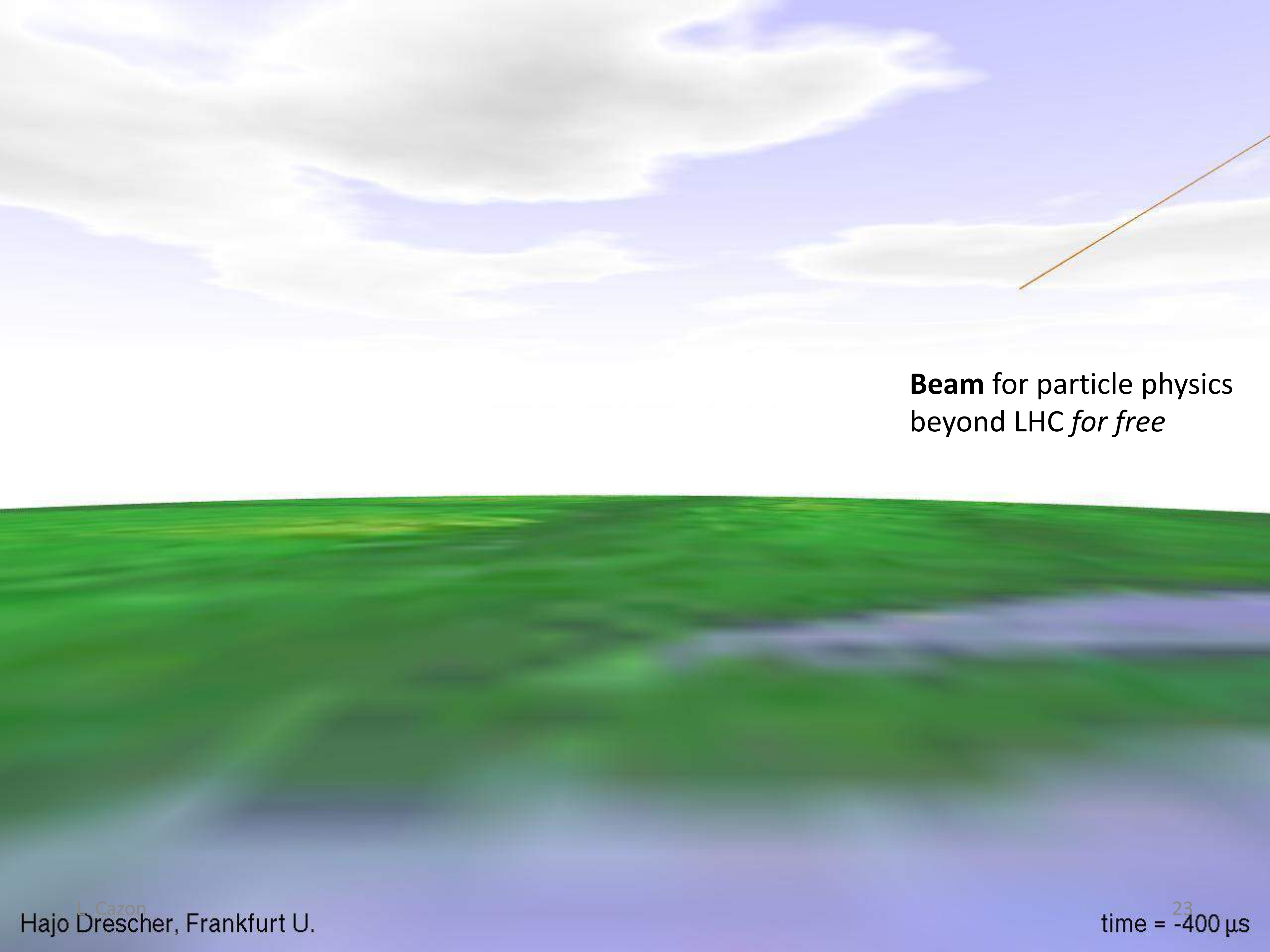
Its **energy, composition, and arrival direction** are the inputs to solve puzzle about their origin



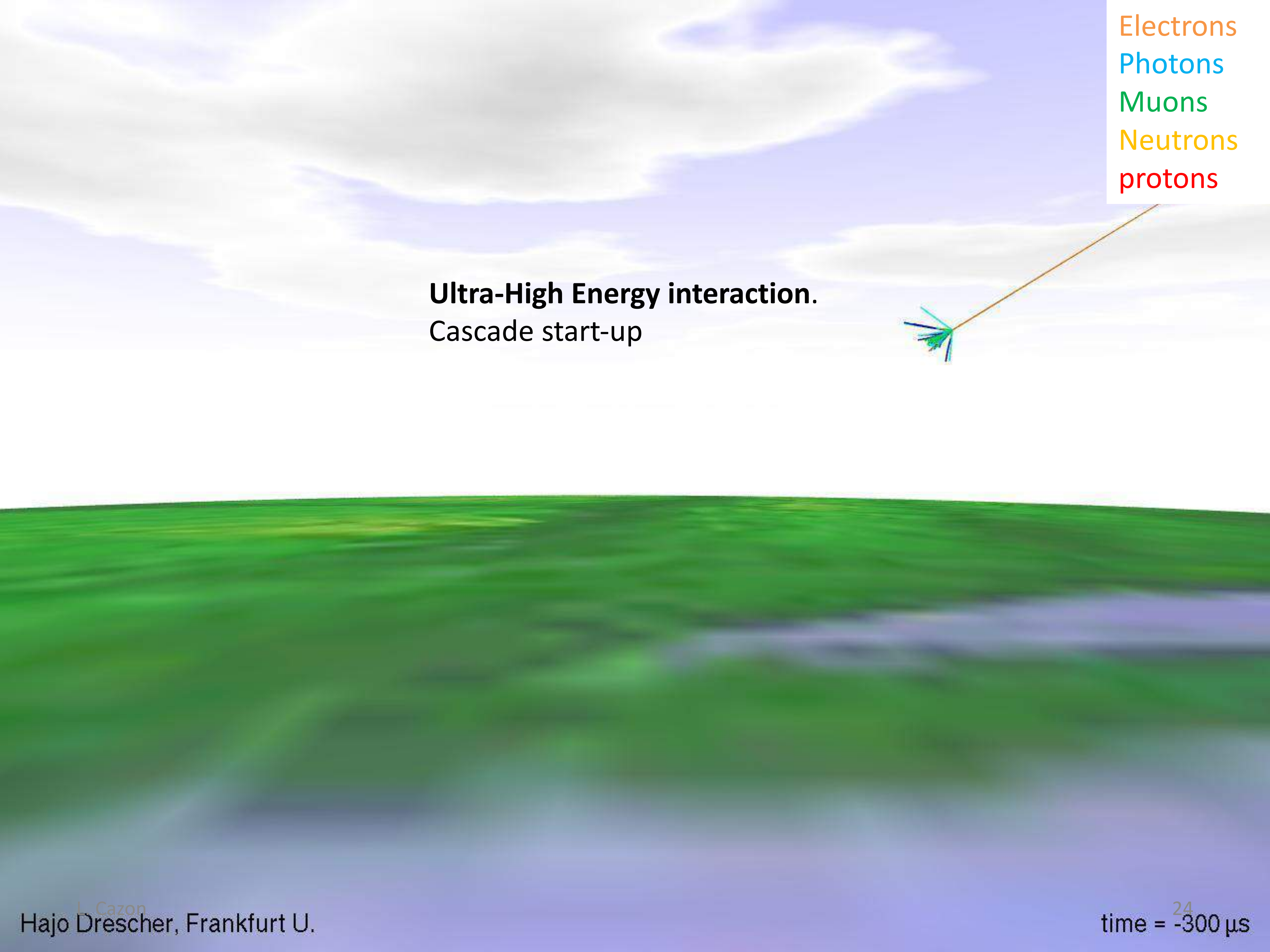
Its **energy, composition, and arrival direction** are the inputs to solve puzzle about their origin



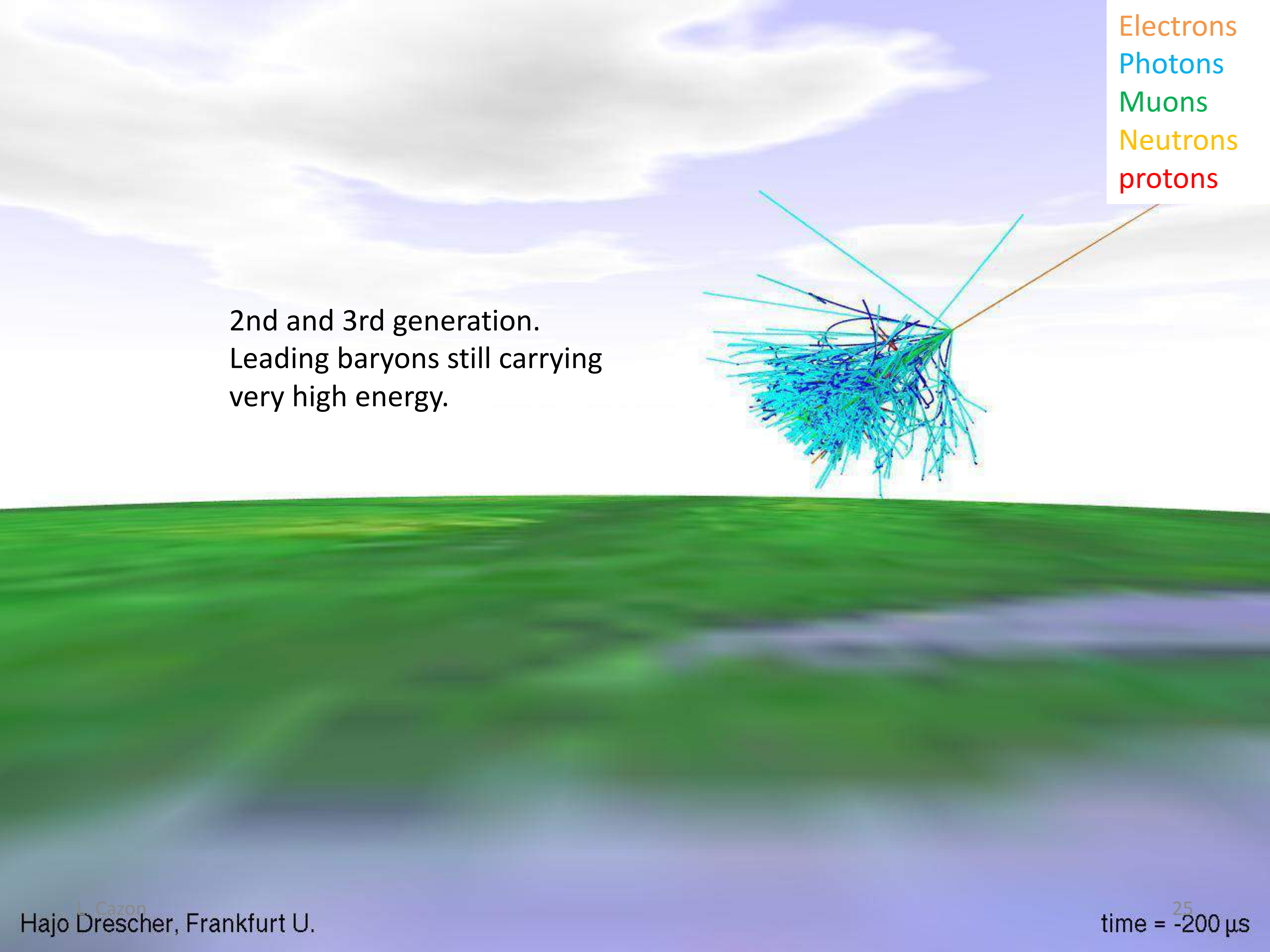
Beam for particle physics beyond LHC *for free*


Beam for particle physics
beyond LHC *for free*
Hajo Drescher, Frankfurt U.
time = -400 µs

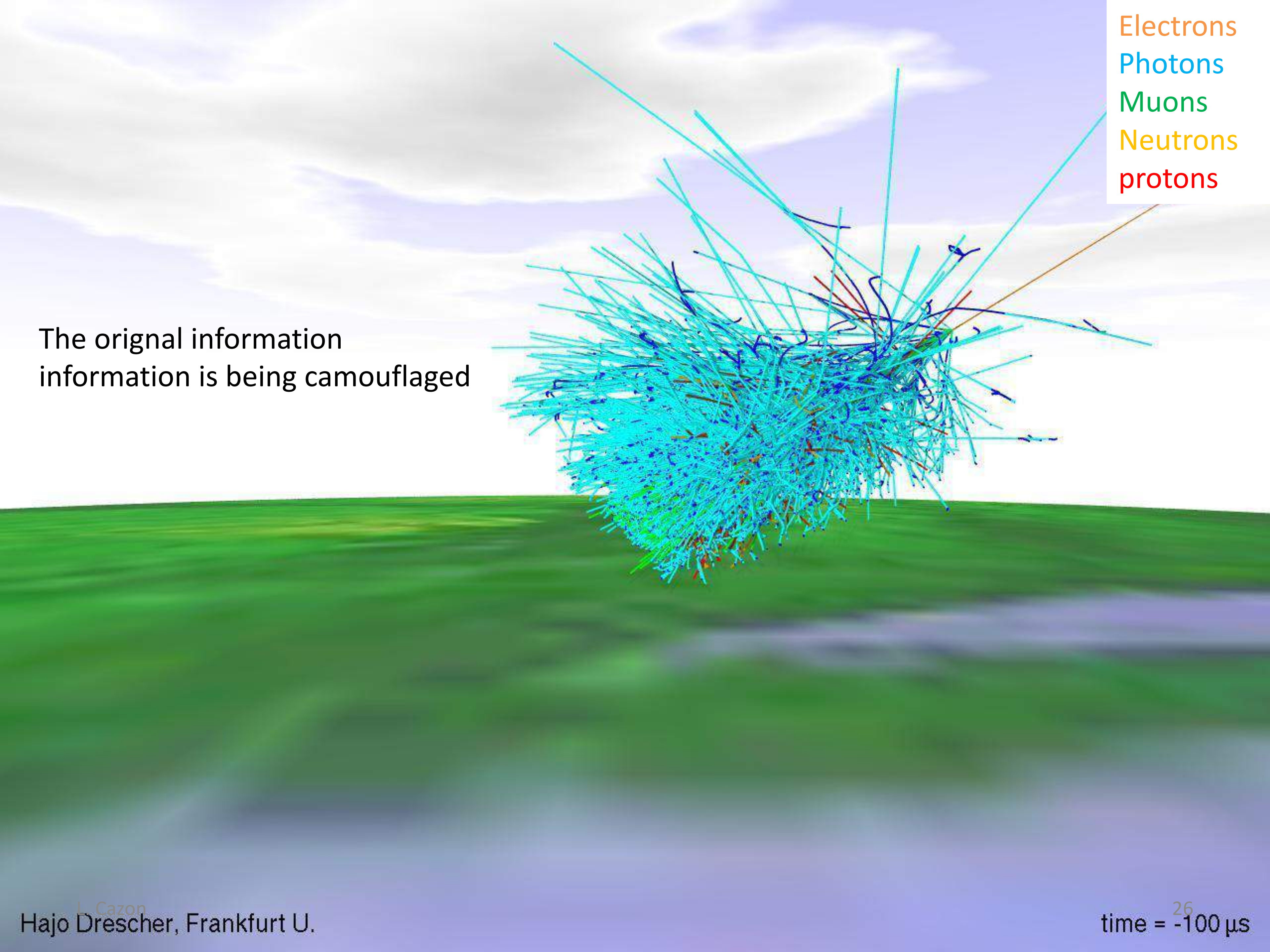
Ultra-High Energy interaction.
Cascade start-up

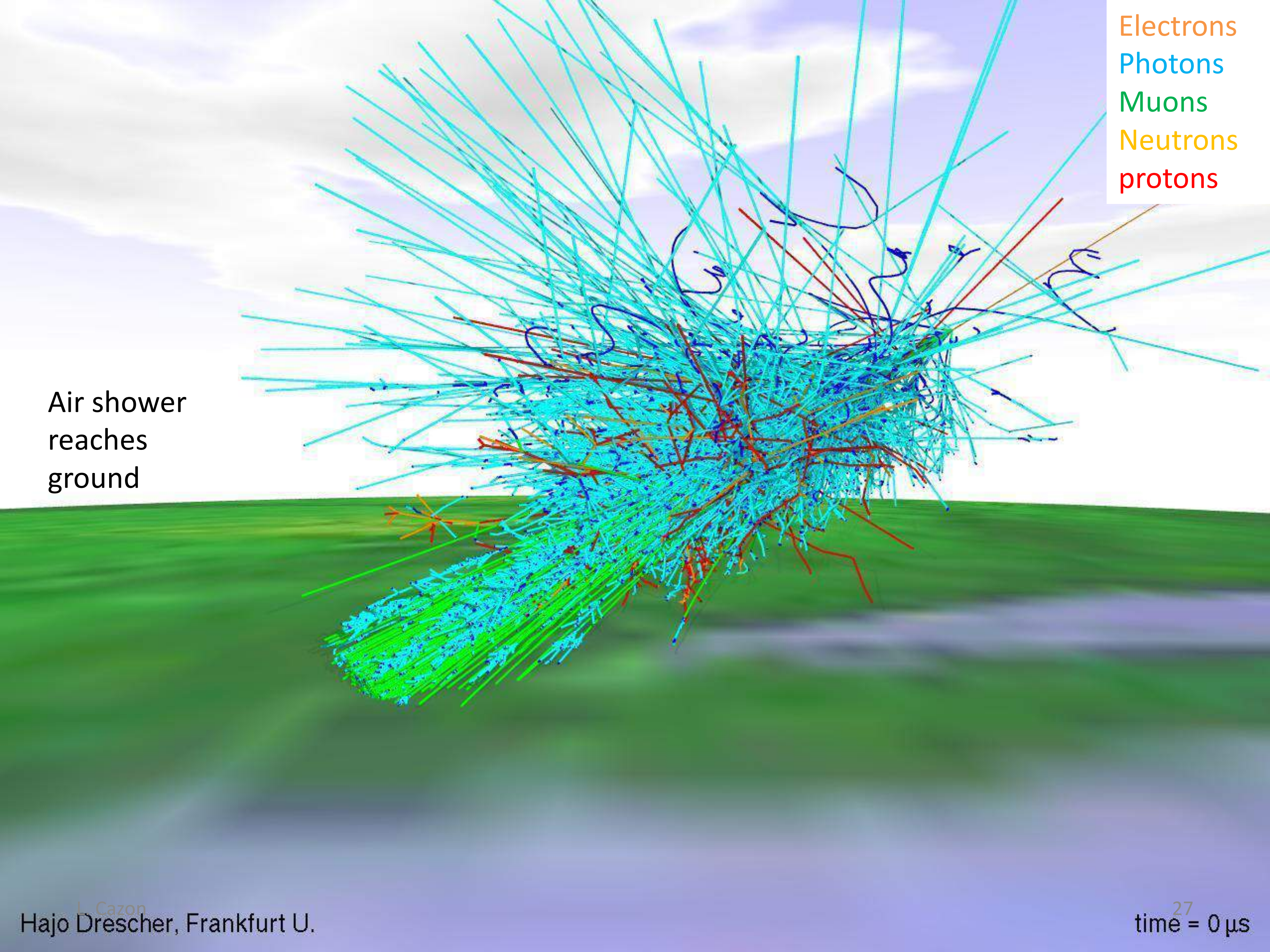


2nd and 3rd generation.
Leading baryons still carrying
very high energy.



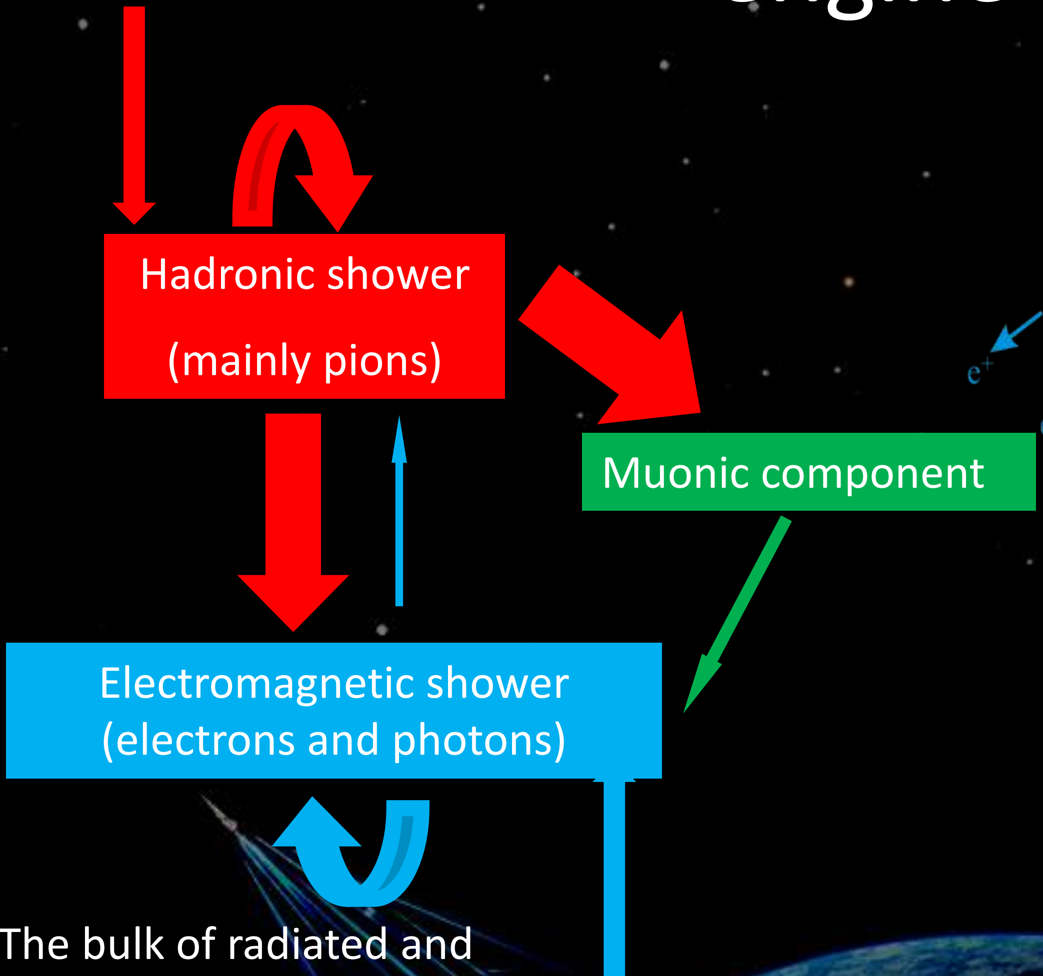
The orignal information
information is being camouflaged




Electrons
Photons
Muons
Neutrons
protons
Air shower reaches ground
Hajo Drescher, Frankfurt U.
time = 0 µs

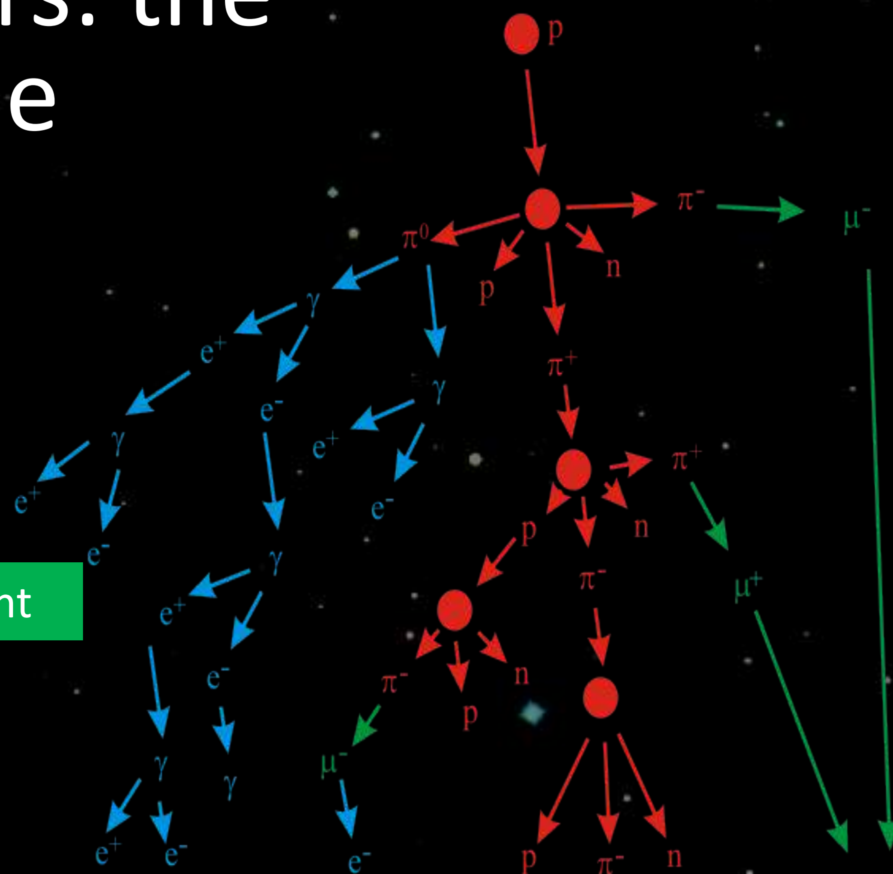
Air Showers: the engine

Primary: Hadron



The bulk of radiated and visible energy comes from the EM cascade

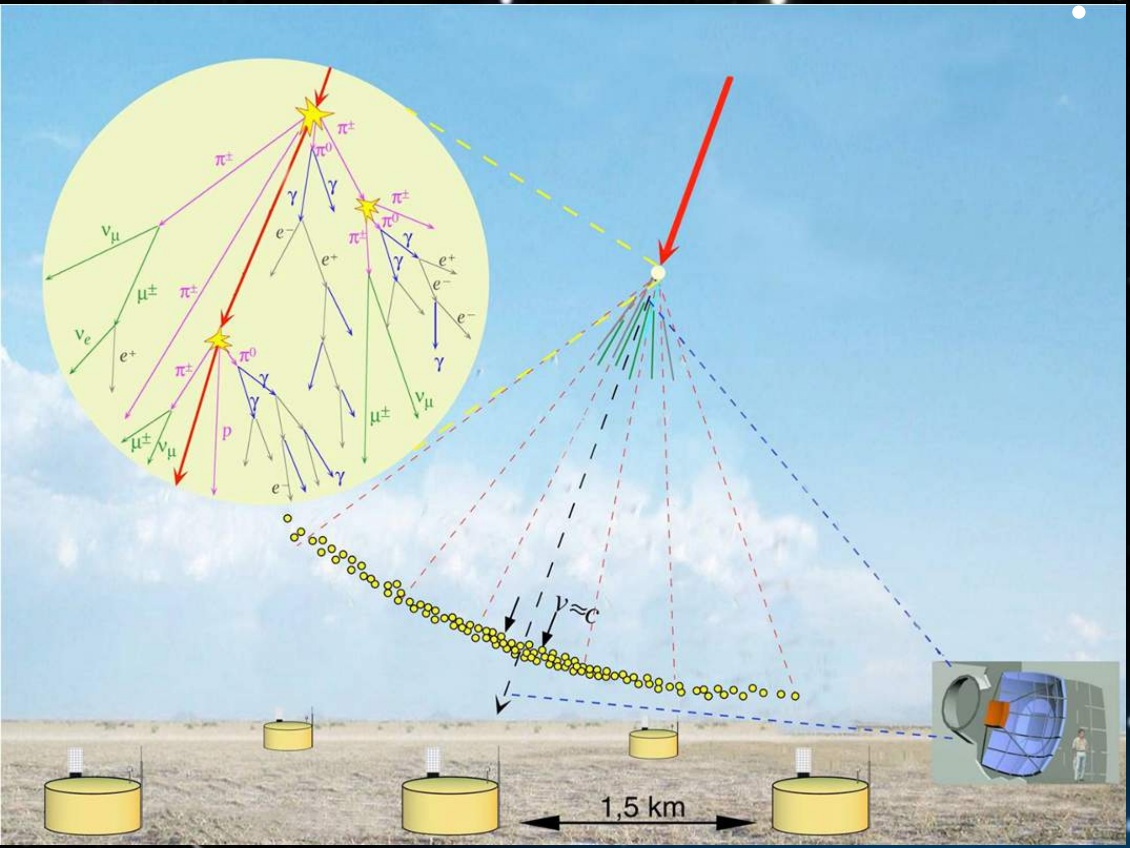
Primary: Photon



Muons are the smoking gun of the hadronic shower which is the real backbone of the whole shower.

π^0 decays are smoking canyons

Extensive Air Shower



- Shower has two experimentally different parts:
  - The core, size of a few m, particle density of 10^9 particles/m2.
    - Interation of particle with the atmosphere produces radiation trhough different mechanisms: Radio emission at MHz (Cerenkov & Geosincrotron), Microwaves GHz (Molecular Bremstrahlung), UV-Cerenkov, UV-fluorescence.
  - The shower pancake: size up 5 km in traverse distance. Density varies from 1 particle/m2, to 10^9 at the core. At 1000 m typical density of the order of 10-1000 particles/m2.

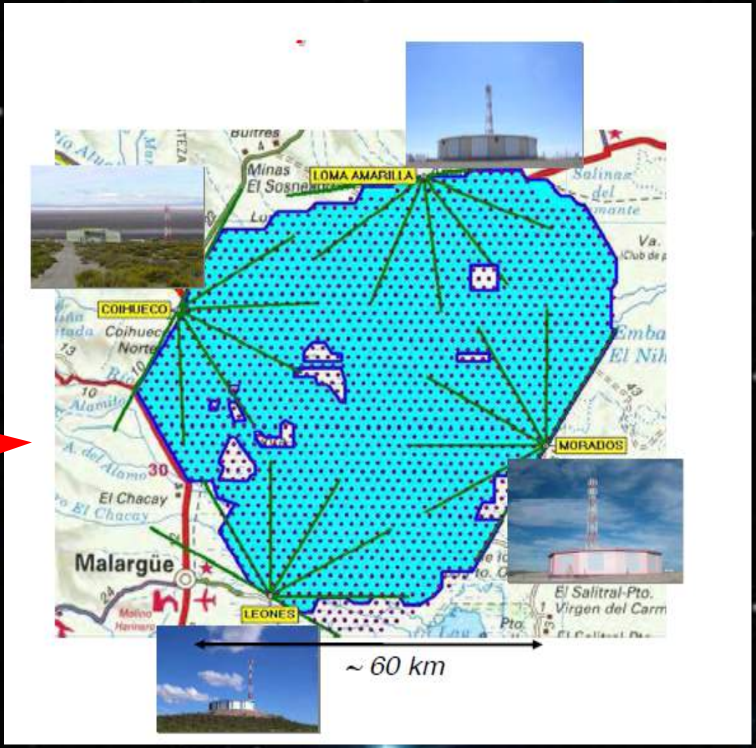
By Johnson Lake in Banff National Park, Canada

This is a real picture

of a fireball. A n Extensive Air Shower would look like that if we could see UV)

The Pierre Auger Observatory

- Malargüe. Mendoza
- Latitude 35 S – Longitude 69 W
- 1400m a.s.l. X=870 g cm^2
- Data taking since 2004
- Installation completed in 2008



Surface Detector (SD)

1600 Cherenkov stations spaced 1.5 km
Area of 3000 km^2
100% duty cycle
Provides Large Statistics

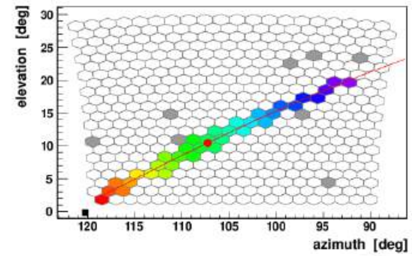
Fluorescence Detector (FD)

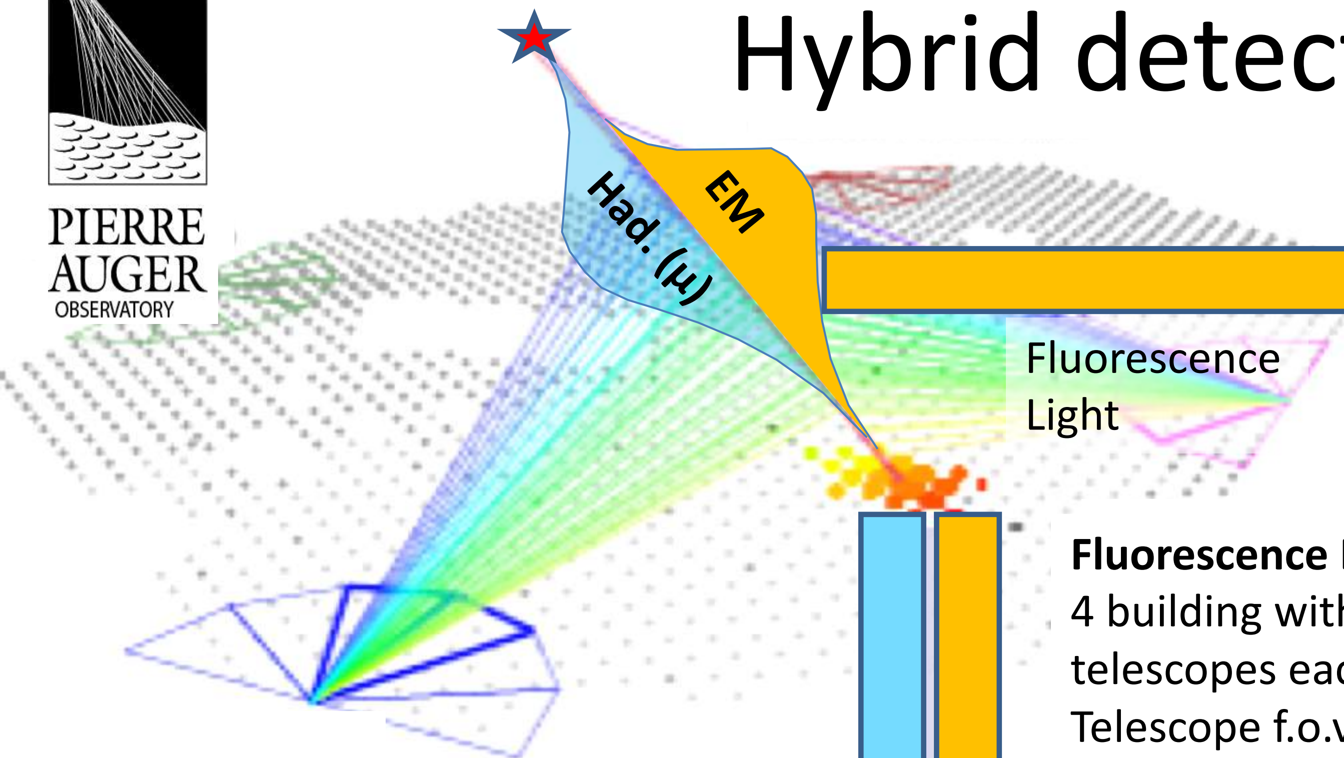
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30 deg
~10% duty cycle
Provides High Accuracy

+ Enhancements: AMIGA, HEAT, Radio, etc

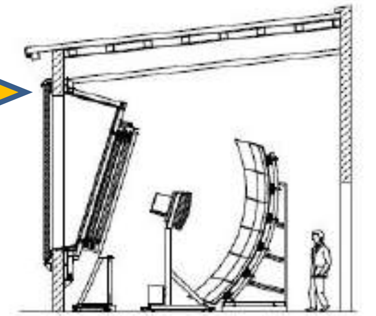


Hybrid detector

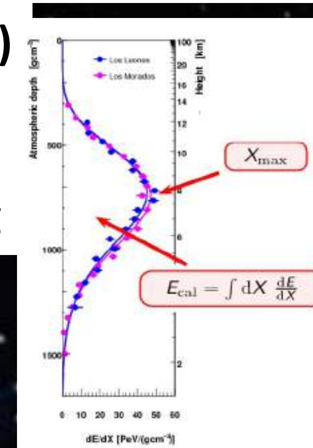




Fluorescence
Light

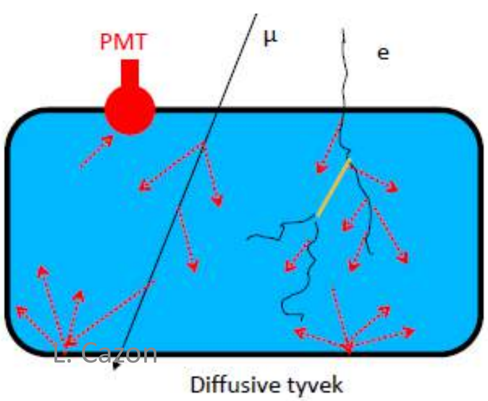


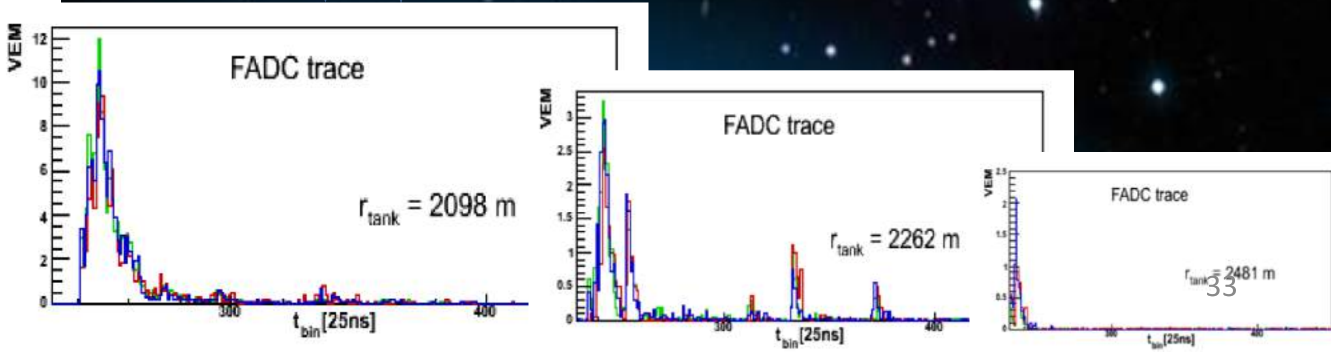
Fluorescence Detector (FD)
4 building with 6
telescopes each
Telescope f.o.v. 30 x 30 deg



Secondary
Particles

Surface Detector (SD)
1600 water Cherenkov tanks
Area of 3000 km^2

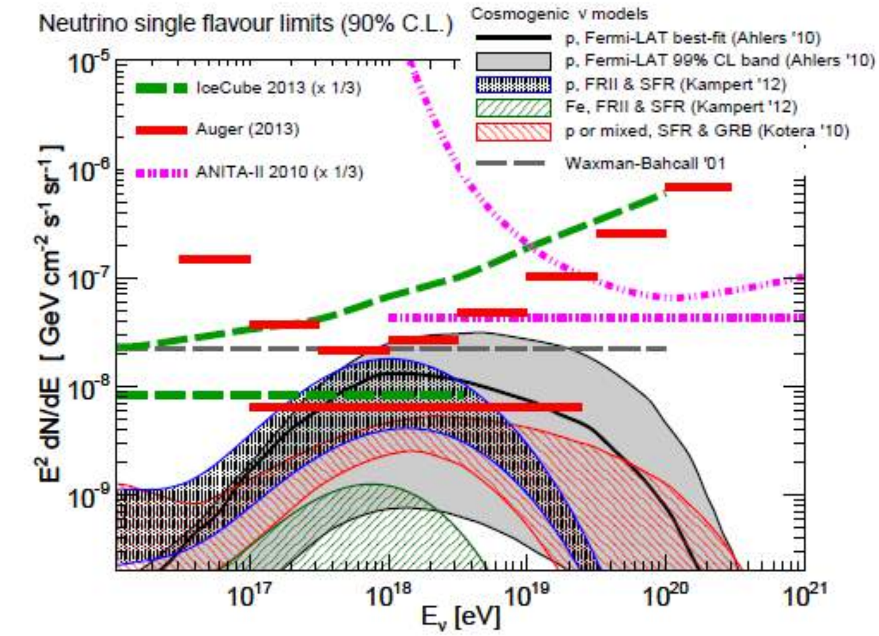


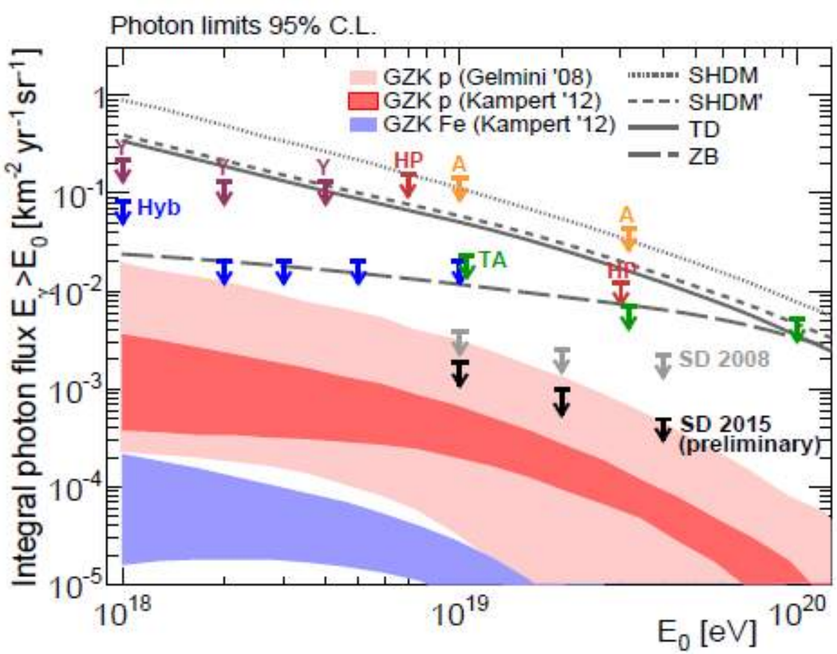


Auger results at a glance

- Photons and Neutrinos
- Anisotropies
- Composition
- Spectrum
- Combined fit. Models

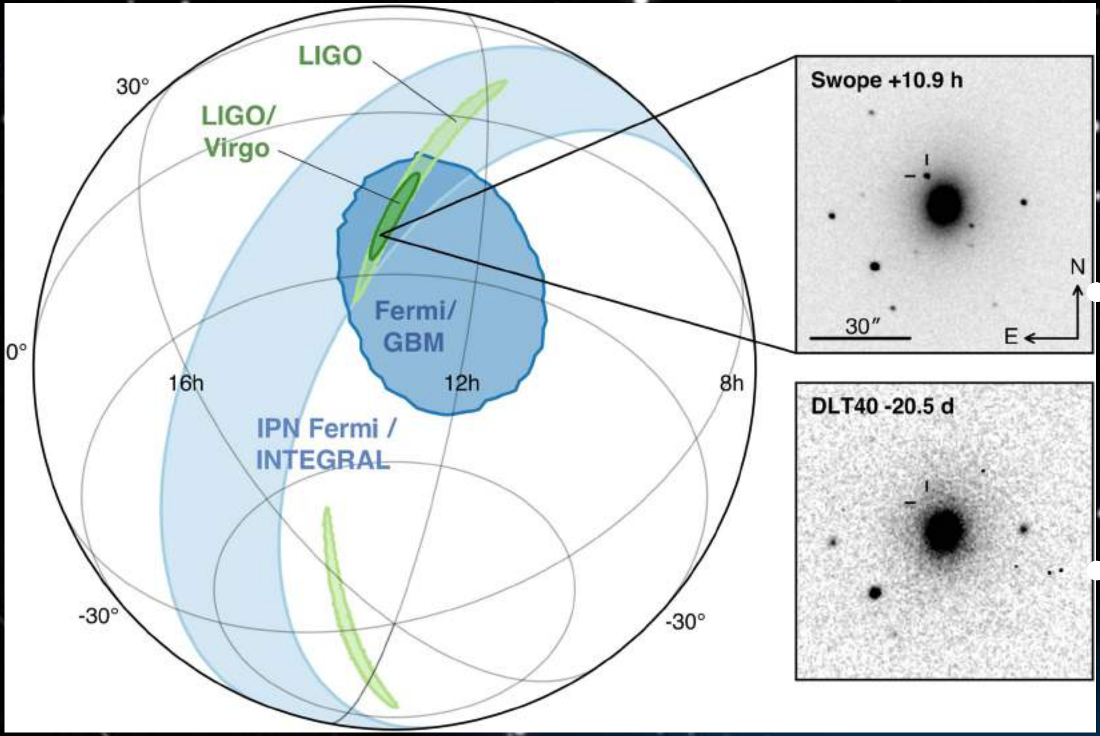
Photon & neutrino fluxes





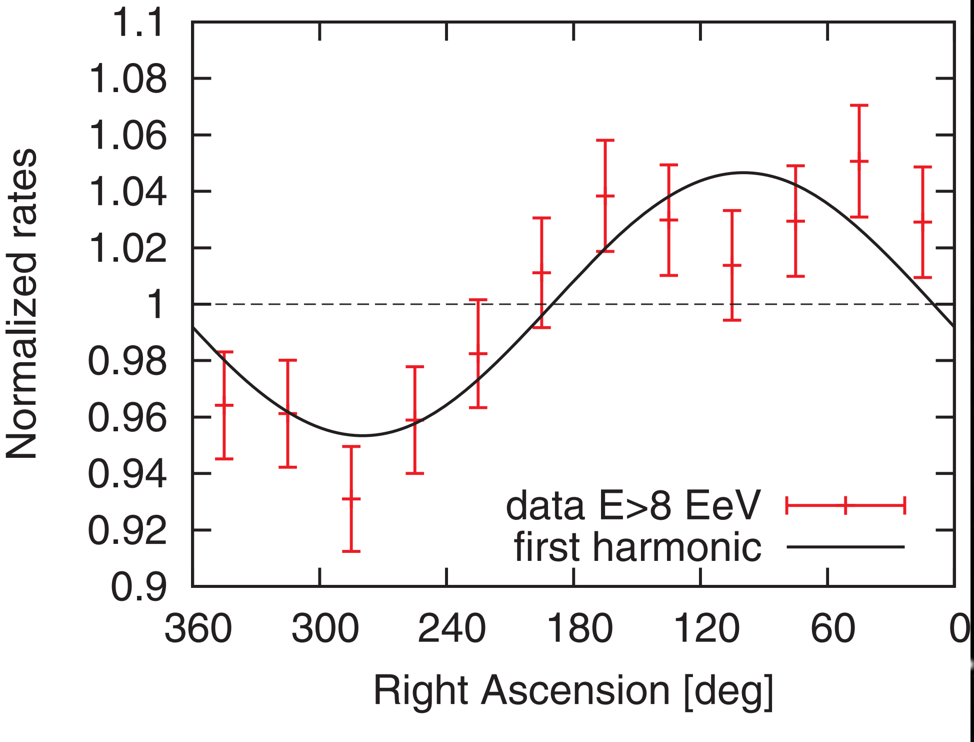
- Observations disfavour most of the exotic decay scenarios to produce UHECR and favour acceleration in astrophysical scenarios
- They are reaching the guaranteed cosmogenic fluxes
- No point sources
- No events associated with interesting objects

Multimessenger Physics



- Observations of a Binary Neutron Star Merger (GW170817)
- Event was in the Auger field of view
- No neutrinos detected

Anisotropy



5.6 σ raw significance

5.2 σ significance after penalizations for E-bin scanning

Need to double statistics to asses if it is a pure dipole or if higher harmonics exist.

Table 1. First harmonic in right ascension. Data are from the Rayleigh analysis of the first harmonic in right ascension for the two energy bins.

Energy (EeV)	Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 8	81,701	0.001 ± 0.005	0.005 ± 0.005	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
≥8	32,187	−0.008 ± 0.008	0.046 ± 0.008	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

3D orientation of the dipole

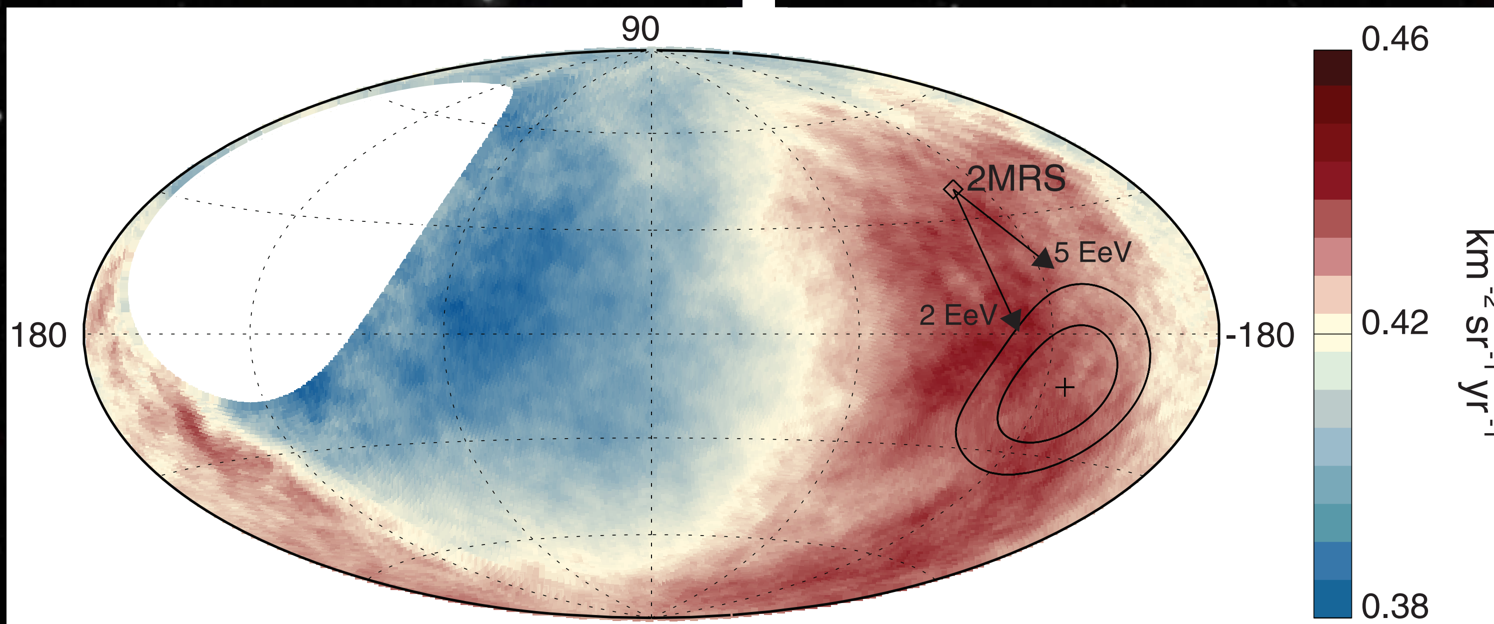
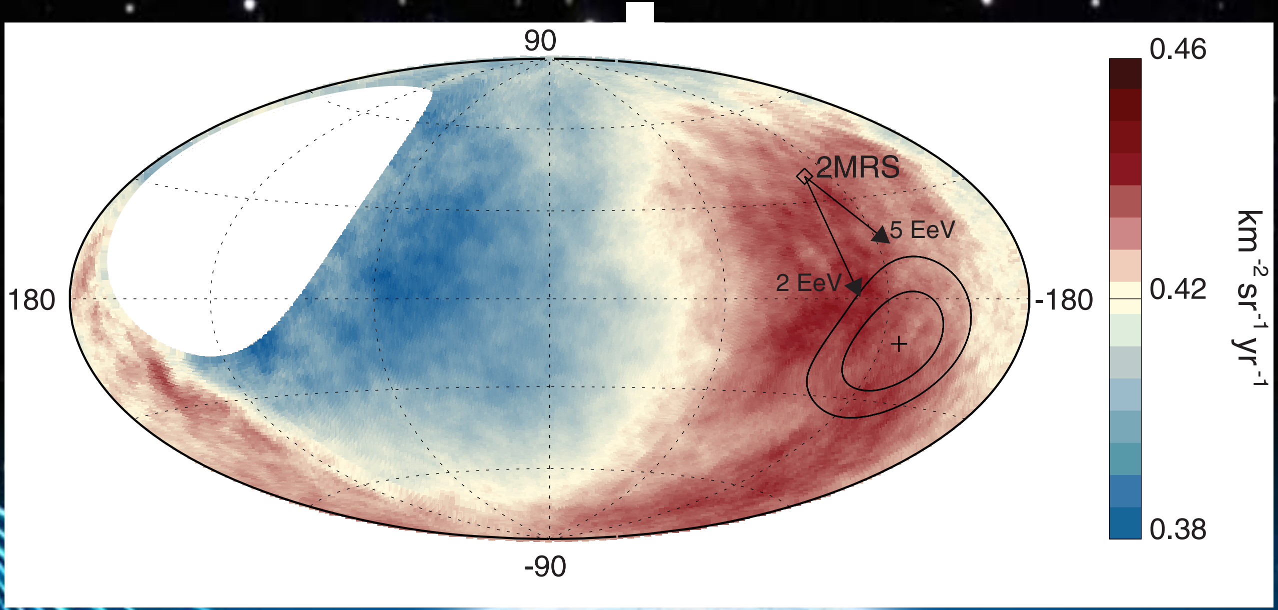


Table 2. Three-dimensional dipole reconstruction. Directions of dipole components are shown in equatorial coordinates.

Energy (EeV)	Dipole component d_z	Dipole component $d_\perp$	Dipole amplitude d	Dipole declination δ_d (°)	Dipole right ascension α_d (°)
4 to 8	-0.024 ± 0.009	$0.006^{+0.007}_{-0.003}$	$0.025^{+0.010}_{-0.007}$	-75^{+17}_{-8}	80 ± 60
≥8	-0.026 ± 0.015	$0.060^{+0.011}_{-0.010}$	$0.065^{+0.013}_{-0.009}$	-24^{+12}_{-13}	100 ± 10

Extragalactic matter

- ~55 deg away from the 2MRS dipole
- If including effects of Galactic Magnetic Field for E/Z=2 EeV and E/Z=5EeV agreement improves



Interpretation

- If EeV sources are Galactic (short GRB or Hyper-Novae), they'd follow the Milky way mass distribution (disc+Galactic Center)
  - stronger dipole would be observed in the 4 EeV < E <8 EeV
  - Above E>8 EeV, the dipole would point close to the Galactic Center (125 deg off now)

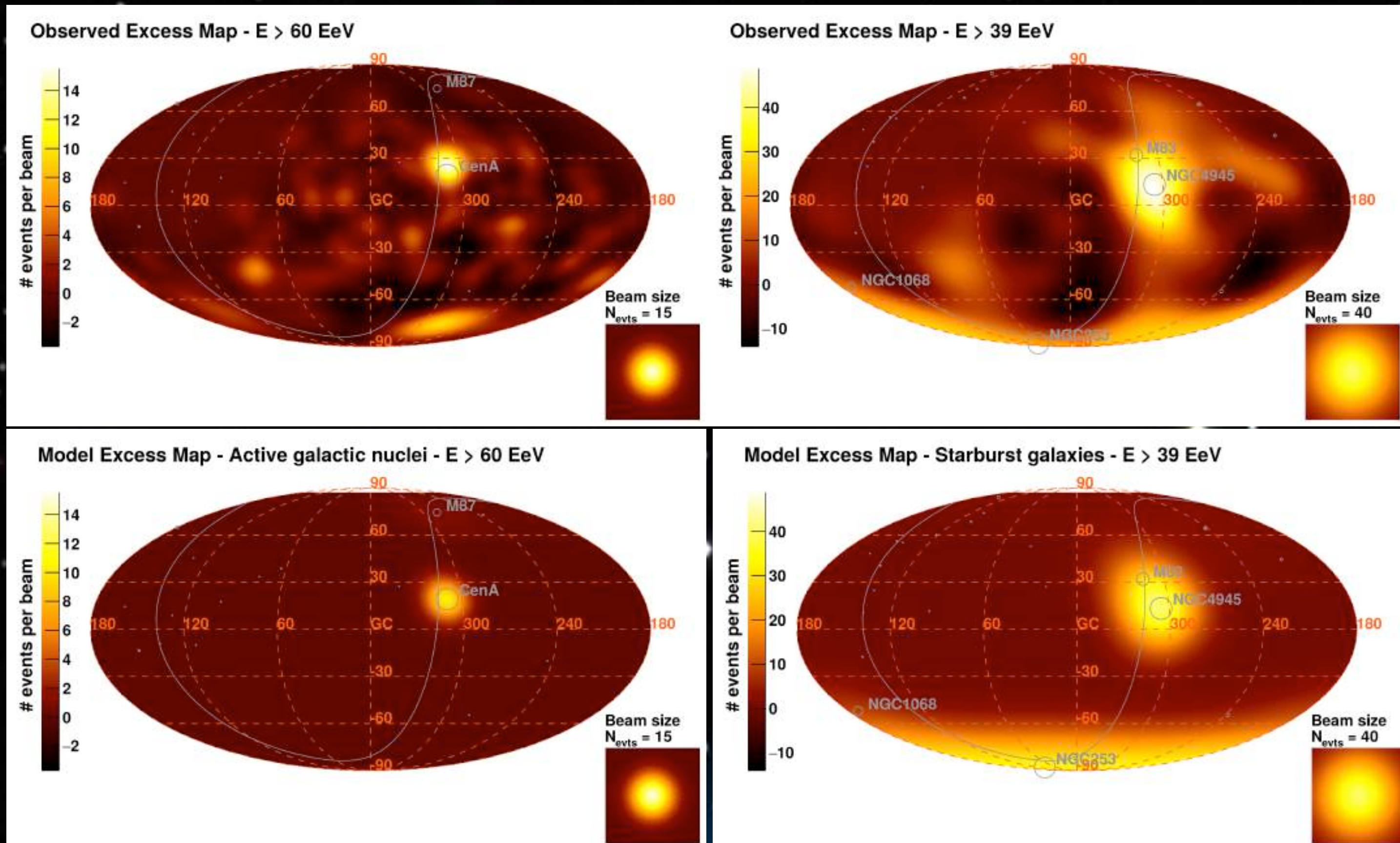
- Anisotropies are better explained if sources are Extragalactic

Interpretation

- Pure known dipoles excluded:
  - Pecular motion induces Compton Getting effect dipole in UHECR: only 0.6% amplitude
- Matter distribution
  - Dominant few sources+difussion in IGMF?
  - Anisotropic extended source distribution?
    - 2MRS distribution + IGMF demonstrate plausible scenarios

Kinematic dipoles	**amplitude**	**l**	**b**	**uncertain**
Sun w.r.t local group		99°	-4°	$\sim 5^{\circ}$
Local group w.r.t CMB		272°	28°	$\sim 5^{\circ}$
Overall CMB	$0.123 \pm 0.001\,\%$	264.4°	48.4°	$< 1^{\circ}$
Hemispherical power anomaly	**amplitude**	**l**	**b**	**uncertain**
Planck 2015	$6.6 \pm 2.1\,\%$	230°	-16°	$\sim 25^{\circ}$
Large-scale-structure dipoles	**amplitude**	**l**	**b**	**uncertain**
2MRS	$12.0 \pm 0.9\,\%$	214°	35°	$\sim 5^{\circ}$
2MASS	$10.4 \pm 0.4\,\%$	268°	0°	$\sim 5^{\circ}$
WISE-2MASS	$5 \pm 1\,\%$	310°	-15°	$\sim 5^{\circ}$
NVSS	$2.7 \pm 0.5\,\%$	215°	16°	$\sim 15^{\circ}$

Hints at the highest energies



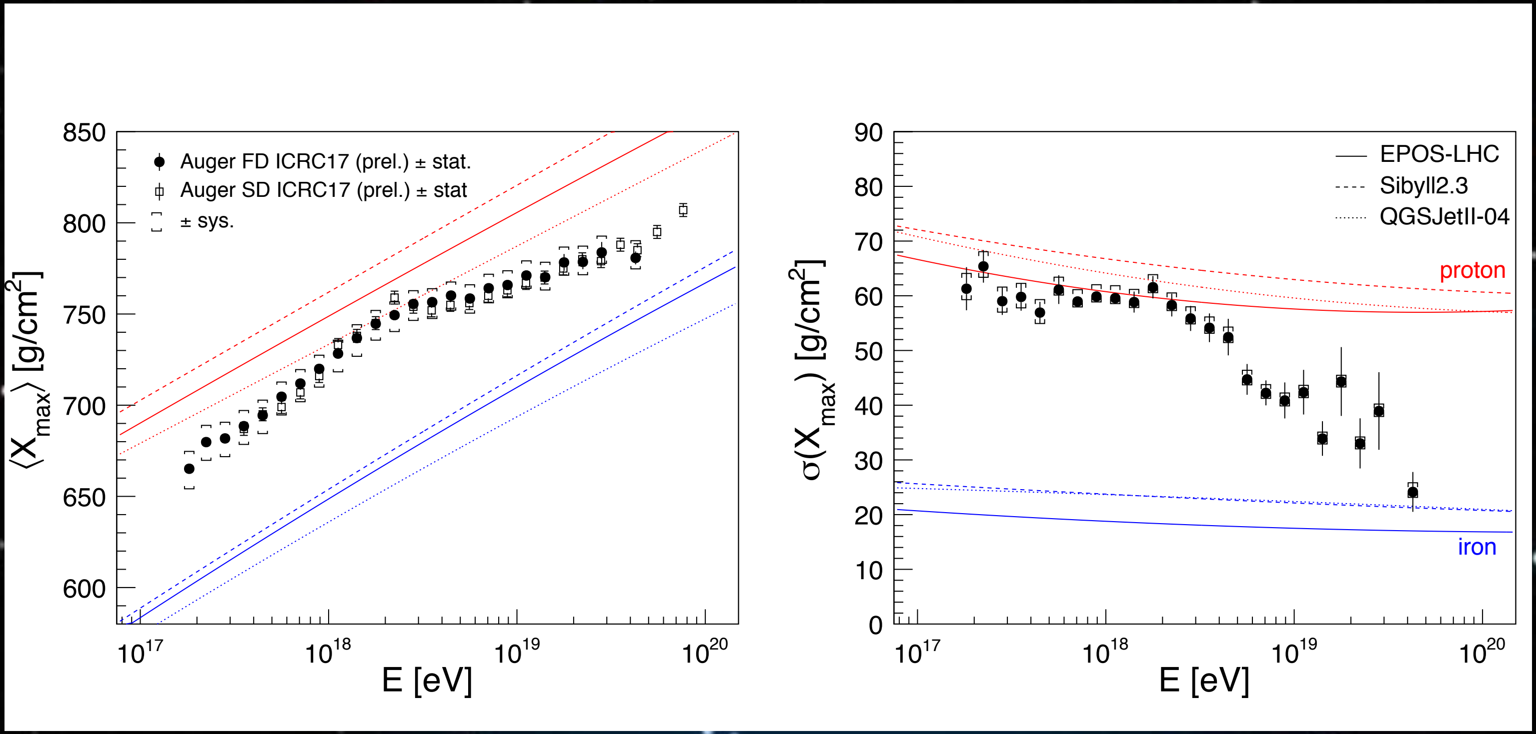
AGN:

Cen A:	E>58 EeV, 15 deg.	3σ
Swift-BAT:	E>62 EeV, 16 deg.	3σ

Fermi-LAT gamma ray sources:

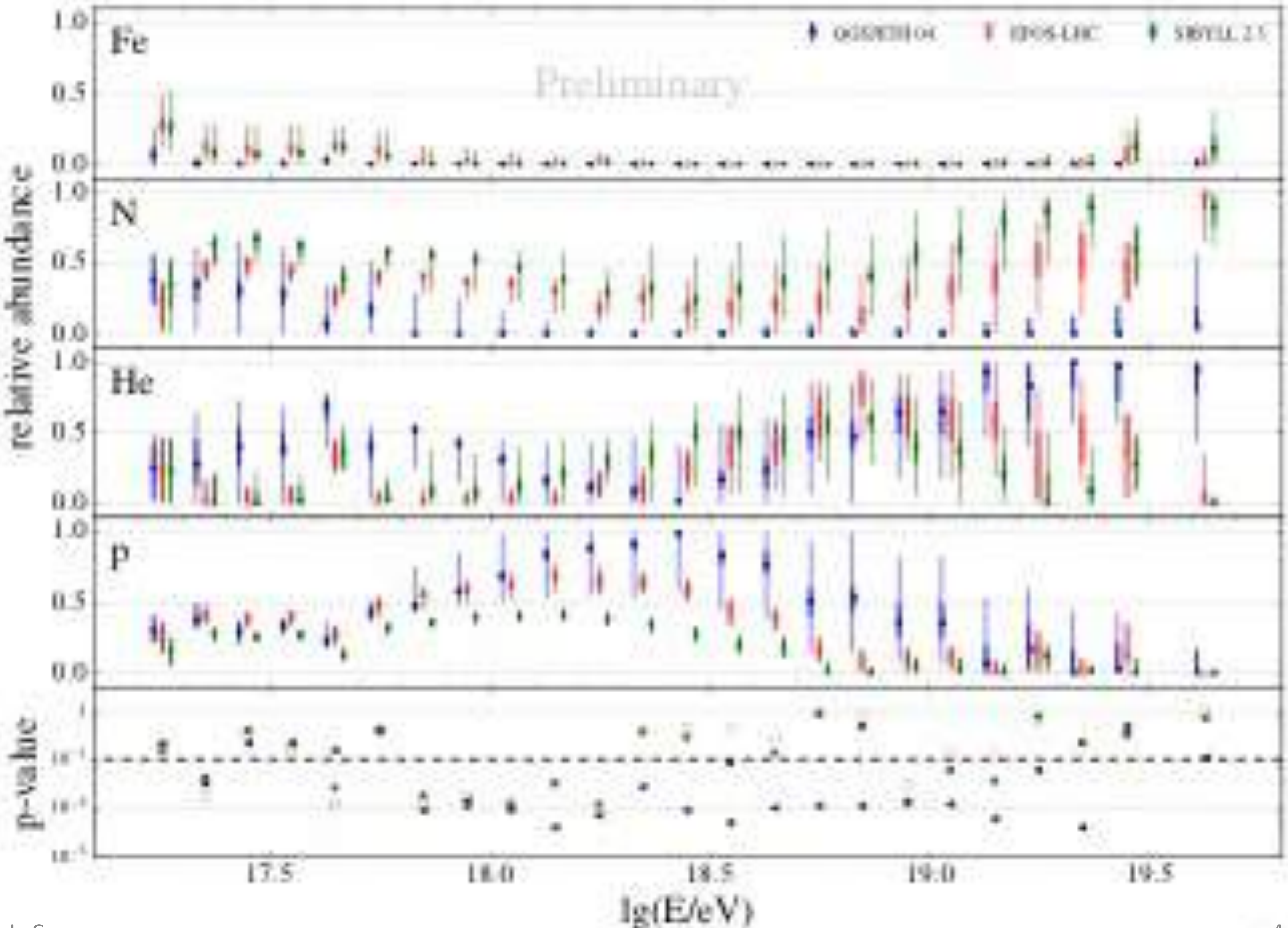
AGN:	E>60 EeV, 7 deg.	2.6σ
Starbust Galaxies	E>39 EeV, 13 deg,	4σ

Composition
(Depth of EM cascade)



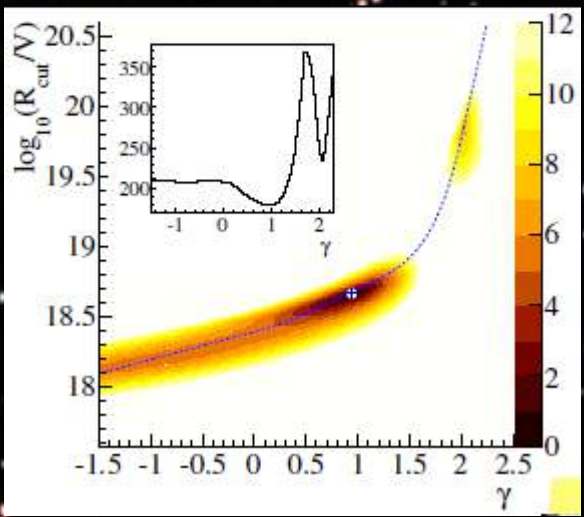
High Metalicity of UHECR (high abundance of A>2 elements)

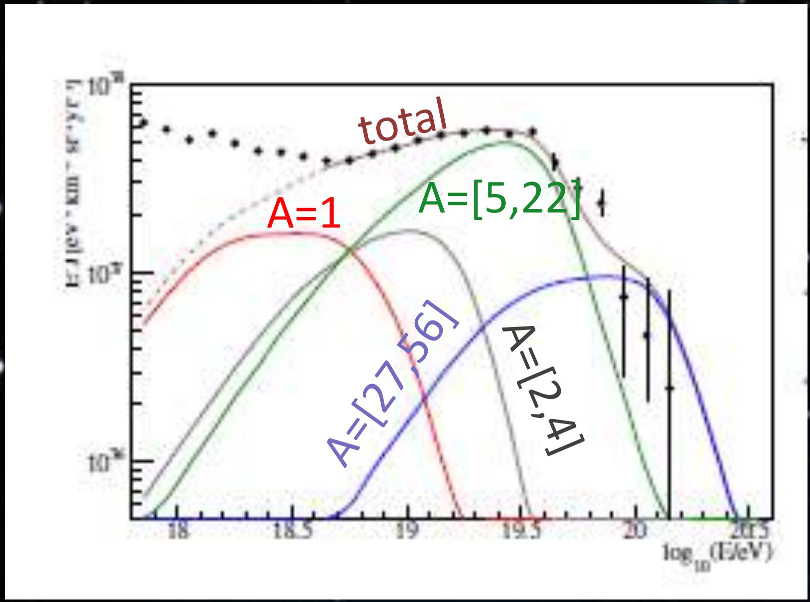
Composition Fractions

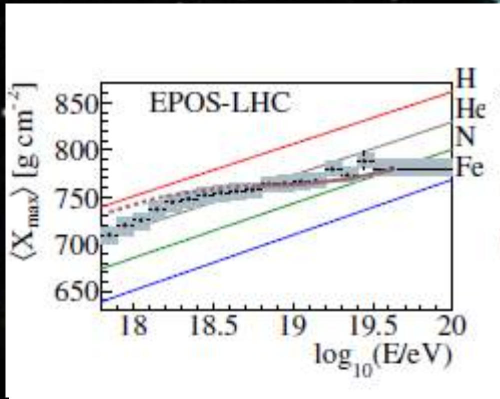


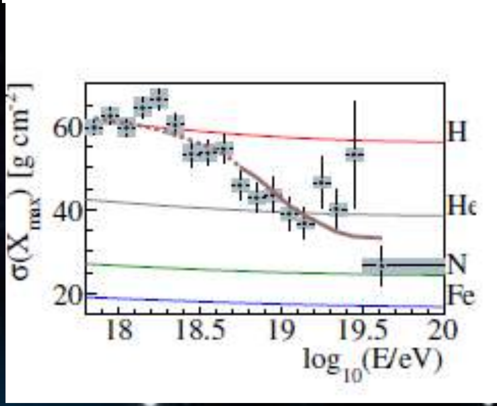
Global fit:

(Simple) Model of UHECR to reproduce the Auger spectrum and Xmax distributions at the same time
Homogeneous distribution of identical sources accelerating p, He, N and Fe nuclei.





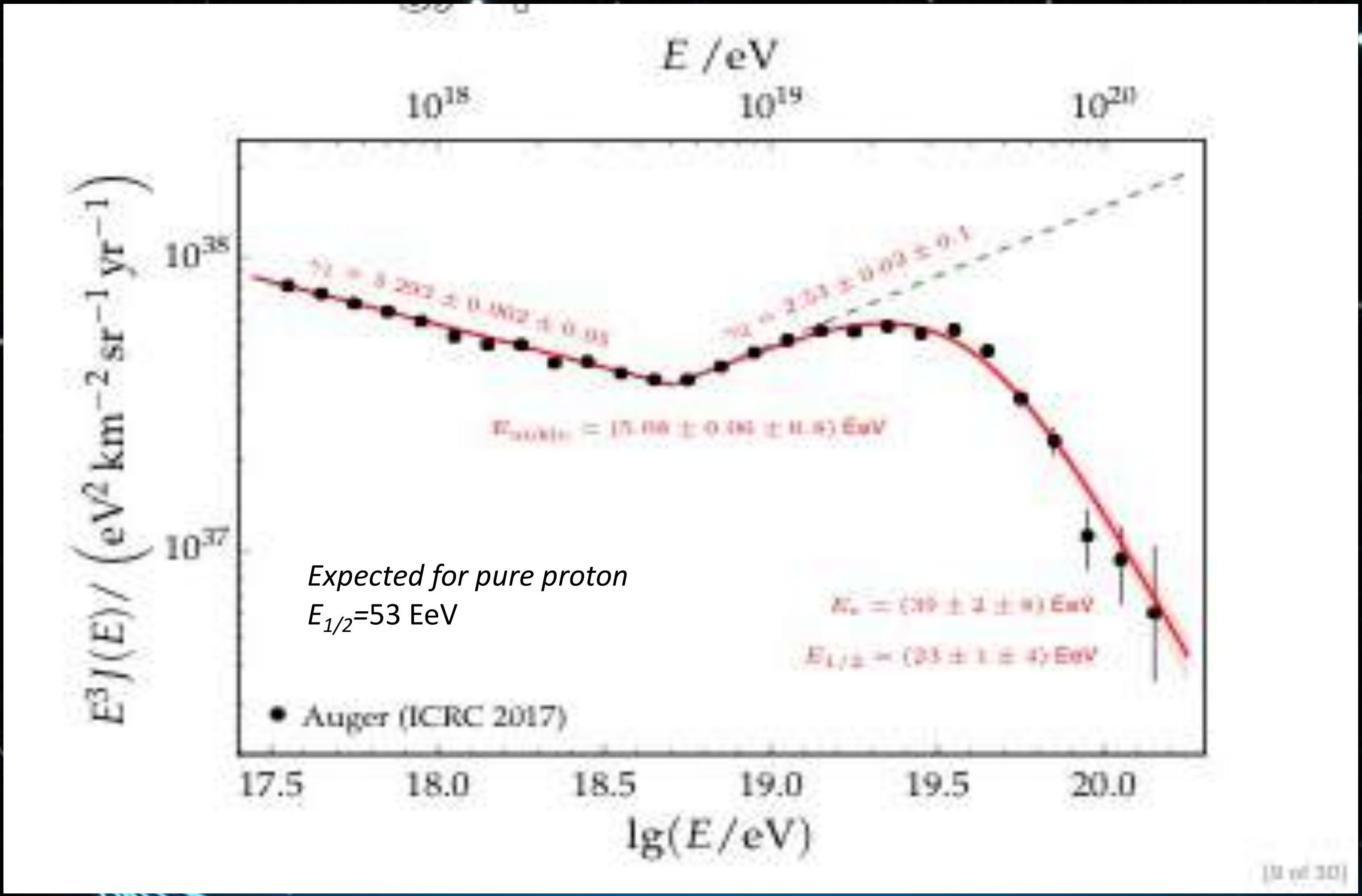




Rigidity-dependent cutoff at source: $E_{max} = R_{cut} Z$, power law injection $E^{-\gamma}$, propagation with CRpropa3, Gilmore12 EBL, Dolag12LSS

Source properties	4D with EGMF	4D no EGMF	1D no EGMF
γ	1.61	0.61	0.87
$\log_{10}(R_{cut}/eV)$	18.88	18.48	18.62
f_H	3 %	11 %	0 %
f_{He}	2 %	14 %	0 %
f_N	74 %	68 %	88 %
f_{Si}	21 %	7 %	12 %
f_{Fe}	0 %	0 %	0 %

E-spectrum



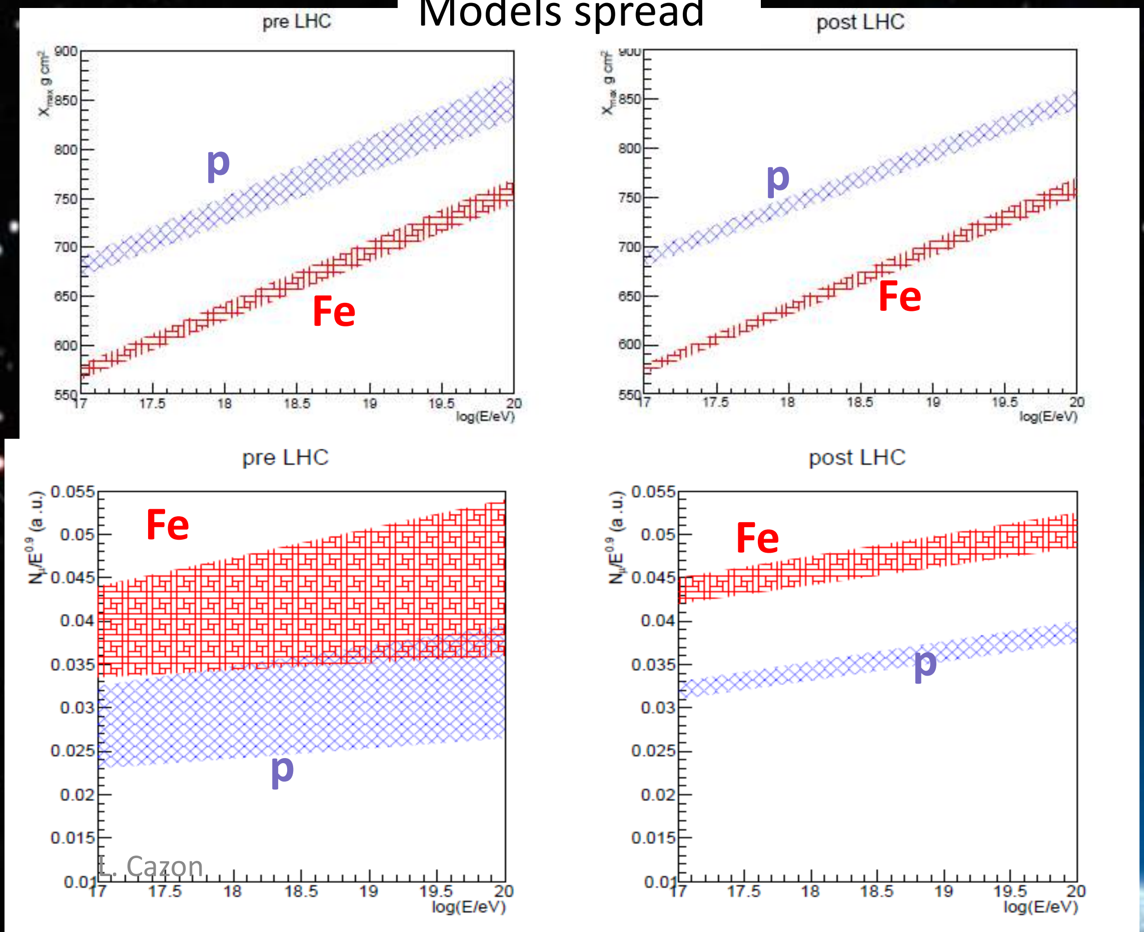
E /eV
10^18
10^19
10^20
10^38
10^37
Expected for pure proton
E1/2=53 EeV
Auger (ICRC 2017)
17.5
18.0
18.5
19.0
19.5
20.0
lg(E/eV)

Conclusions (I)

- 1. All-particle spectrum: unquestionable existence of a flux suppression above ≈ 40 EeV (GZK-reminiscent)
- 2. **Trend towards a heavier composition at the highest energies (from Xmax data, very few** data above 40 EeV). Spectrum and Xmax data together favors the scenario where the suppression is a source effect. **NEED FOR MASS COMPOSITION DATA IN THE SUPPRESSION REGION - ACCESSED BY THE SURFACE DETECTOR**
- 3. Stringent photon limits strongly disfavor exotic sources: astrophysical sources expected.
- 4. But a high degree of (small-scale) isotropy observed, challenging the original expectation of few sources and light primaries. **NEED TO SELECT LIGHT PRIMARIES FOR DOING COSMIC-RAY ASTRONOMY**

We must use air shower simulations performed with High Energy Hadronic Models extrapolated beyond the LHC to interpret our data.

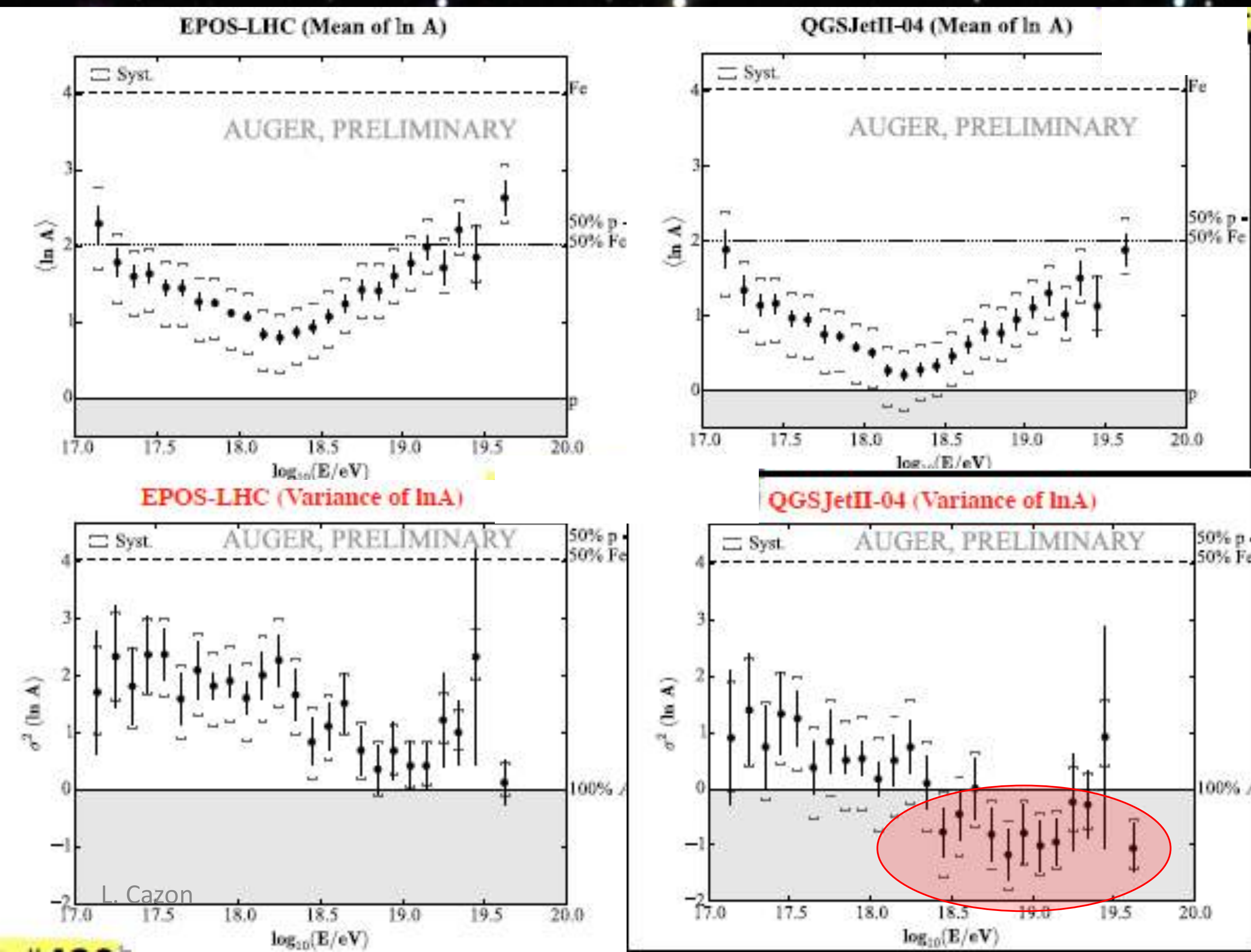
Models spread



Models spread extrapolations has been reduced after LHC measumrements. There are still differences among models.

Extrapolations venture out orders of magnitude out of the confort zone.

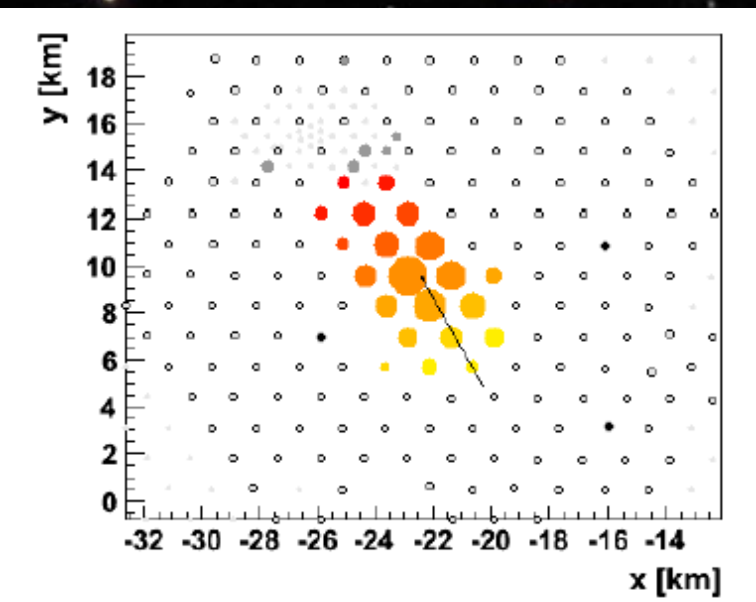
Models show contradictions in the interpretation of Xmax

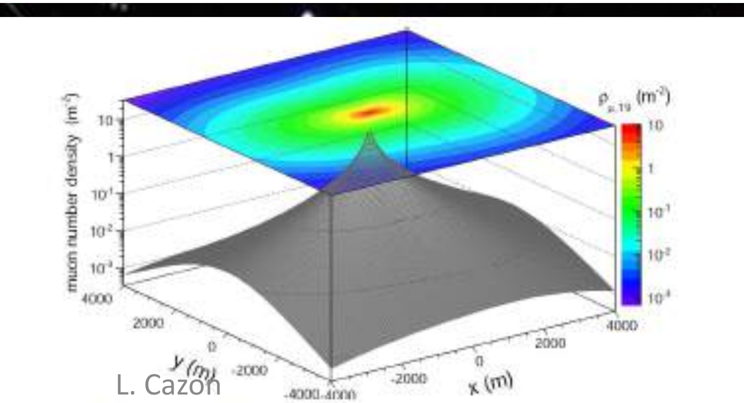


Xmax distributions are not well predicted by some models. Leading to unphysical results. (QGSJetII-04)

Inclined hybrid events

62<Θ<80 deg





Example of $\rho_{\mu,19}$ for proton showers at θ=80°, ϕ=0° and core at (x,y) = (0,0)

Fit the muon density in stations

$$\rho_\mu = N_{19}\rho_{\mu,19}(x,y)$$

where N_{19} free parameter
And $\rho_{\mu,19}$ *(x,y)* is fixed, corresponding to proton QGSJetII-03 at 10^{19} eV

Ratio of the total number of muons N_μ to $N_{\mu,19}$ (proton QGSJetII-03 at 10^{19} eV)

$$R_\mu = N_\mu / N_{\mu,19}$$

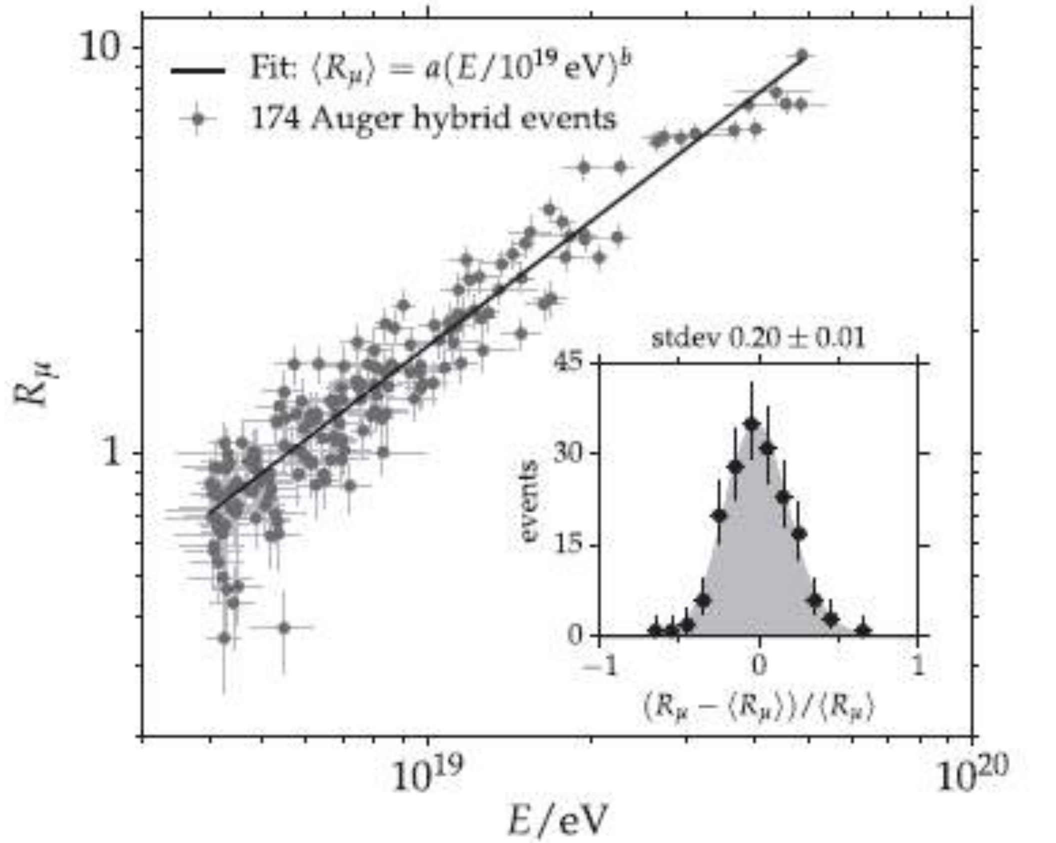
Correspondence (<5% bias correction)

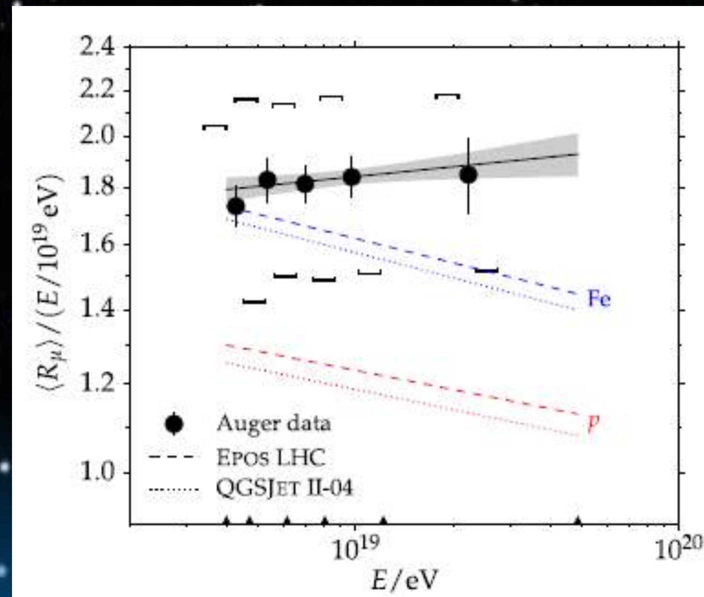
$$N_{19} \Leftrightarrow R_\mu$$

Rmu-E plot: results

PHYSICAL REVIEW D **91**, 032003 (2015)

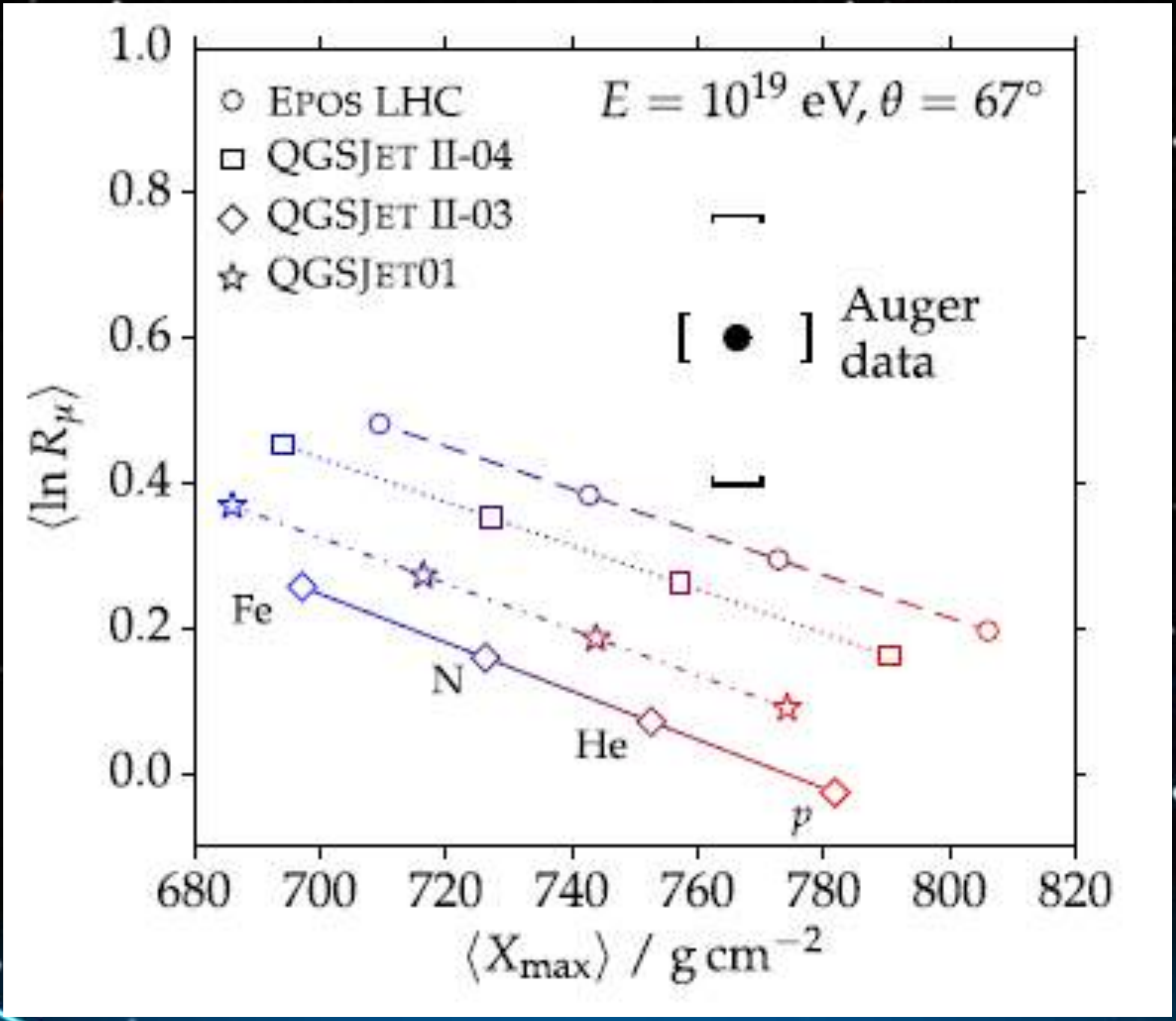
$$N_\mu = A\left(\frac{E/A}{\xi_c}\right)^\beta,$$





$a = \langle R_\mu \rangle(10^{19}\ \mathrm{eV}) = (1.841 \pm 0.029 \pm 0.324(\mathrm{sys})),$

$b = \mathrm{d}\langle \ln R_\mu \rangle/\mathrm{d}\ln E = (1.029 \pm 0.024 \pm 0.030(\mathrm{sys})),$


EPOS LHC
QGSJET II-04
QGSJET II-03
QGSJET01
$E = 10^{19}$ eV, $\theta = 67°$
Auger data
Fe
N
He
p
$\langle \ln R_\mu \rangle$
$\langle X_{max} \rangle$ / g cm^{-2}
1.0
0.8
0.6
0.4
0.2
0.0
680
700
720
740
760
780
800
820

Muon production depth

Muon Production Depth profile can be estimated from the muon arrival times distributions

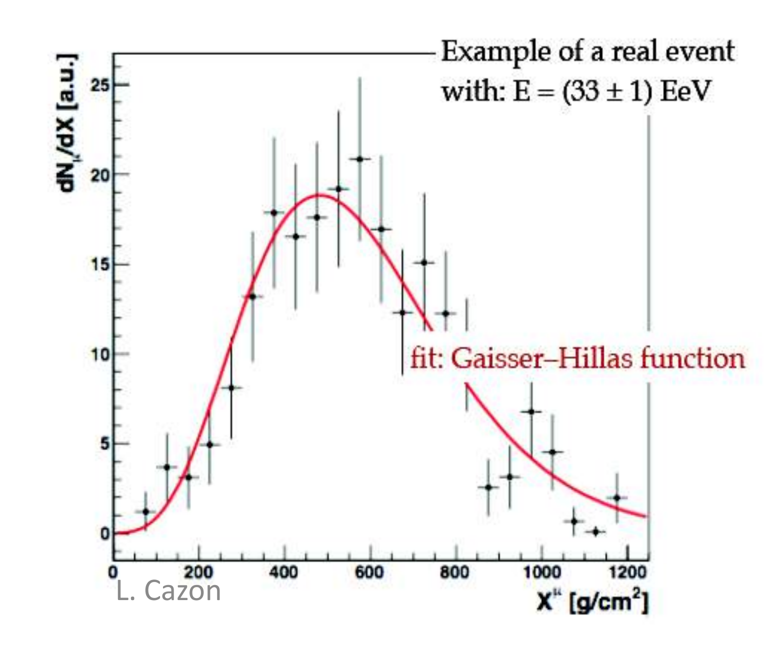
Two assumptions:

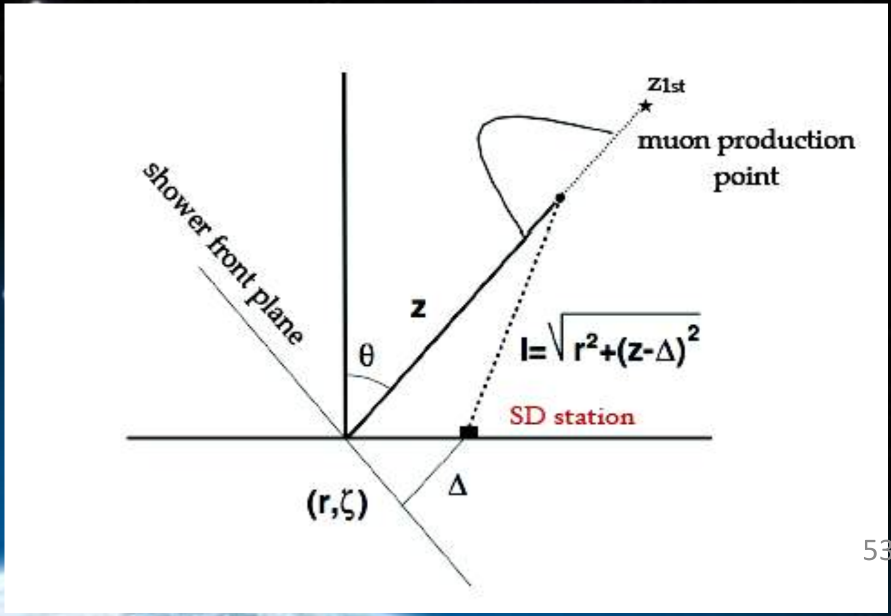
♦ Muons are produced in the shower axis

♦ Muons travel following straight lines

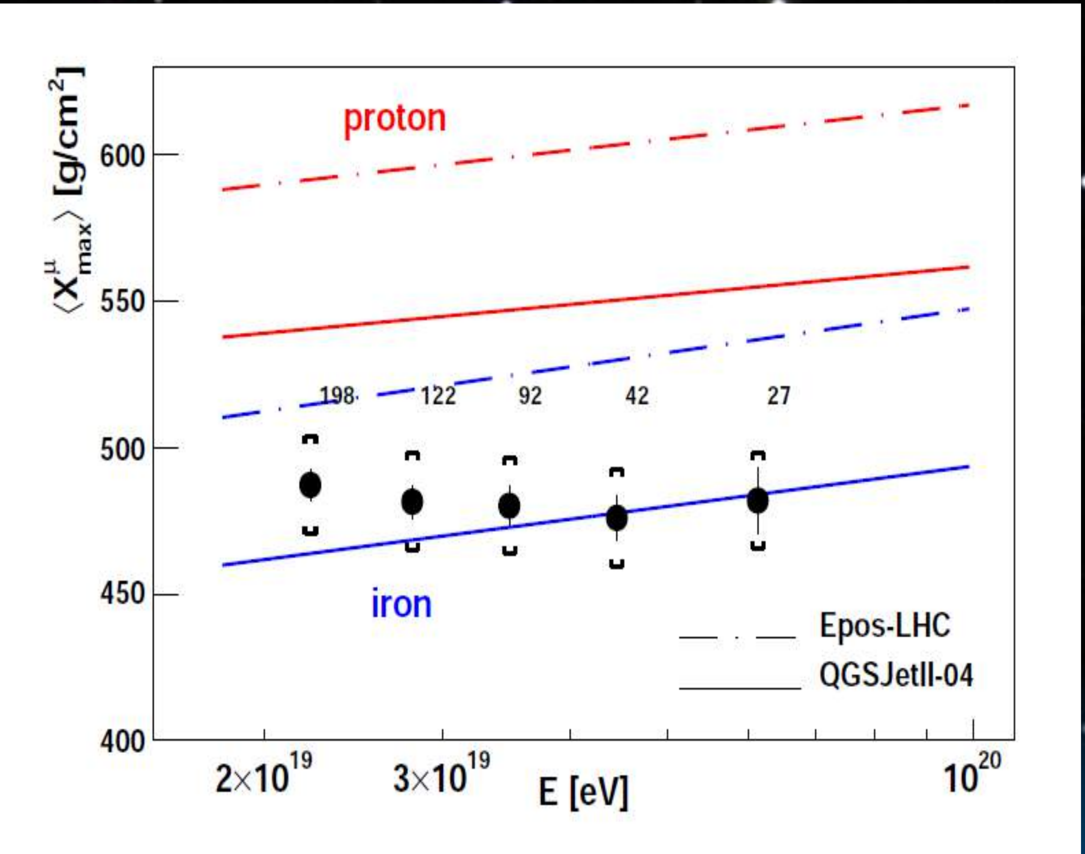
Map from t to z muon by muon

$$z \simeq \frac{1}{2}\left(\frac{r^2}{c(t-\langle t_\epsilon \rangle)} - c(t-\langle t_\epsilon \rangle\right) + \Delta$$





X^{μ}_{max} vs. energy



data set: 01/2004 – 12/2012

E > 1e19.3 eV

zenith angles [55°,65°]

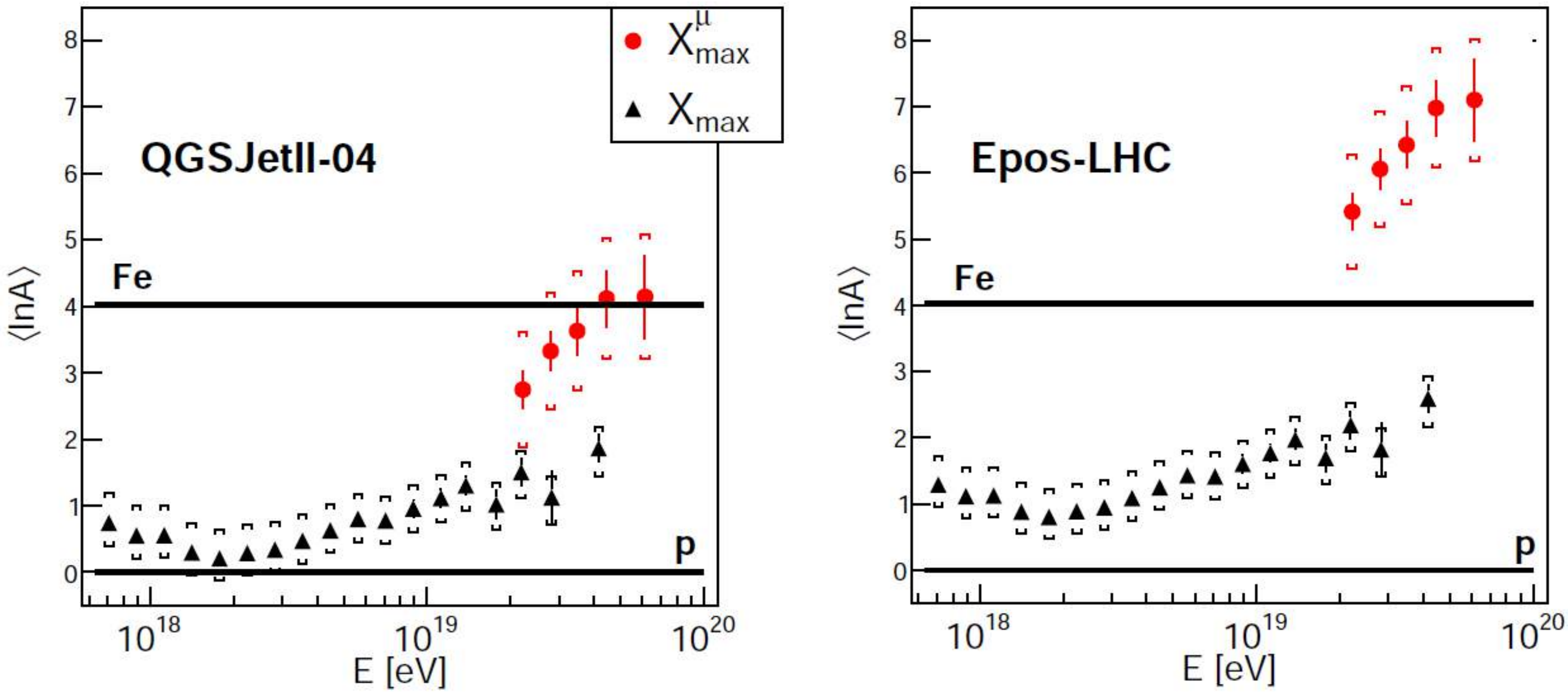
Core distances [1700 m, 4000 m]
(more muons/event)

481 events after quality cuts

syst: 17 g/cm2
Event by event resolution:
100 (80) g/cm2 at 1e19.3 eV for p (Fe)
50 g/cm2 at 1e20 eV

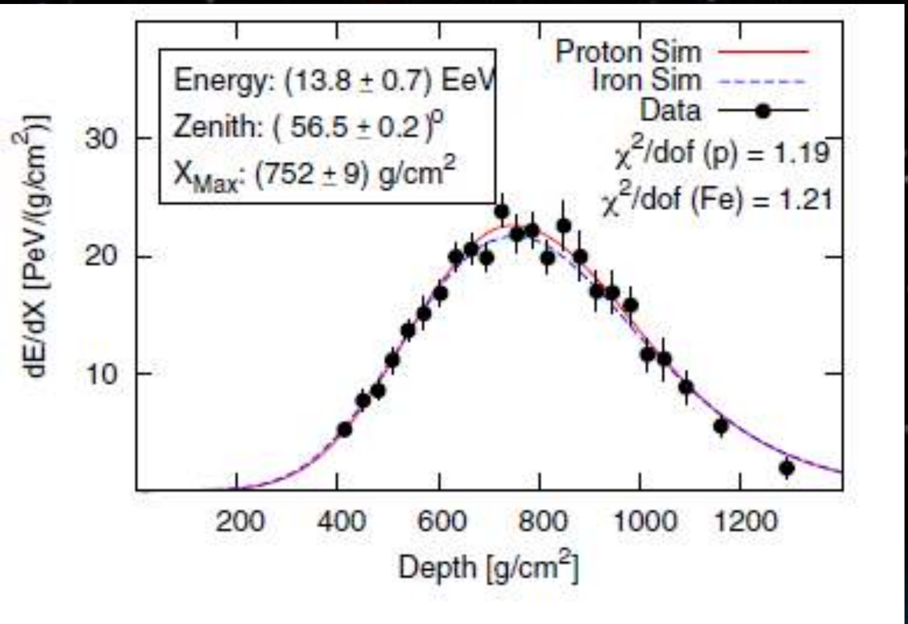
- QGSJetII-04: data bracketed by predictions
- EPOS-LHC: predictions above data

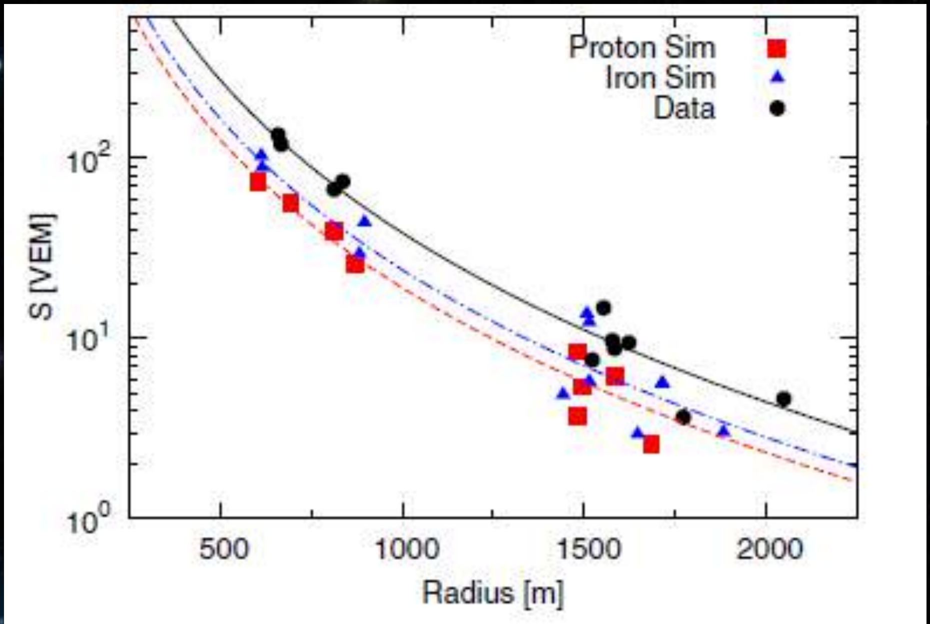
Compatibility between X_{max} and X^{μ}_{max}



- QGSJetII-04: compatible values within 1.5 σ
- EPOS-LHC: incompatibility at a level of at least 6 σ

Independent confirmation with vertical hybrids





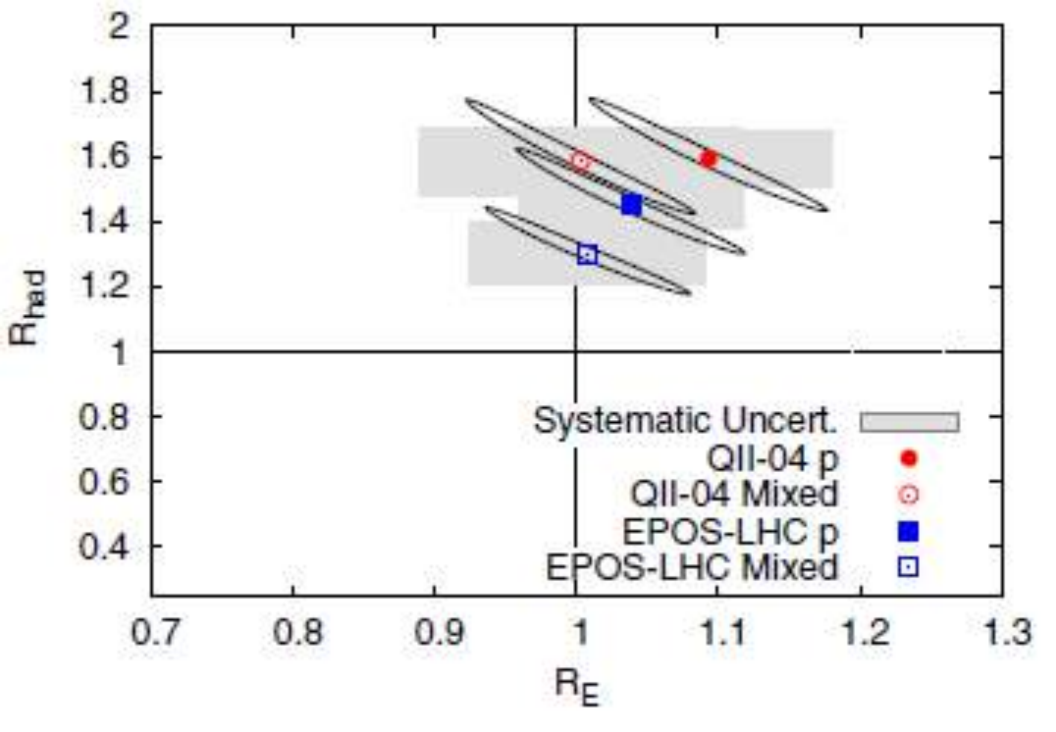
Indentifying the discrepancy

$$S_{\text{resc}}(R_E, R_{\text{had}})_{i,j} \equiv R_E S_{\text{EM},i,j} + R_{\text{had}} R_E^{\alpha} S_{\text{had},i,j}.$$

- R_E: Energy rescaling. Rescales EM and hadronic components
- R_{had}: Hadronic rescaling: rescales muons, EM muon halo, EM from Had.Jets.
- Find R_E & R_{had} for best overall fit

$$Likelihood = \prod_i \sum_j p_j(X_{\max,i})\, Gaus\left(S_{resc}(R_E, R_{had})_{i,j} - S_{1000,i}\right)$$

Results



- **No energy rescaling is needed**

- The observed muon signal is a factor 1.3 to 1.6 larger than predicted by models

- Smallest discrepancy for EPOS-LHC with mixed composition, at the level of 1.9 σ

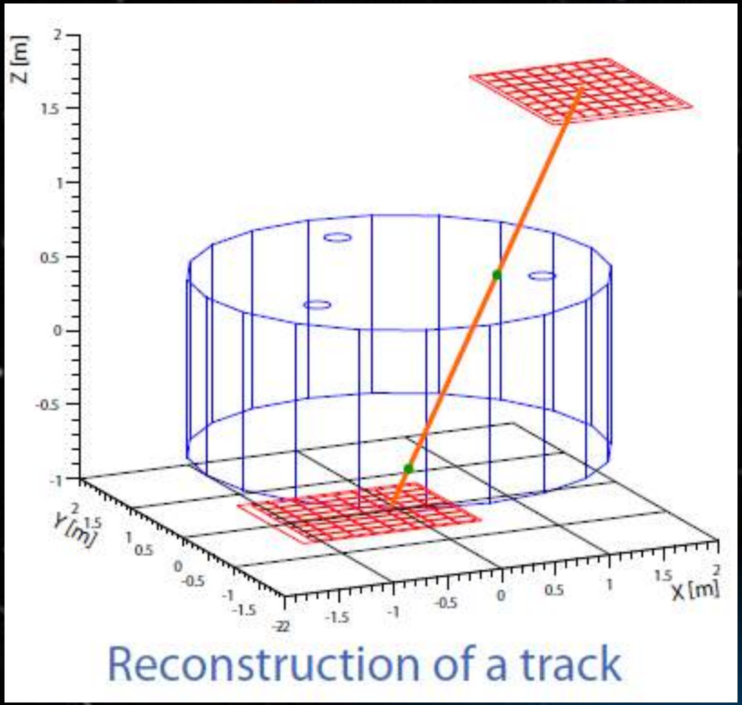
Model	R_E	R_{had}
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

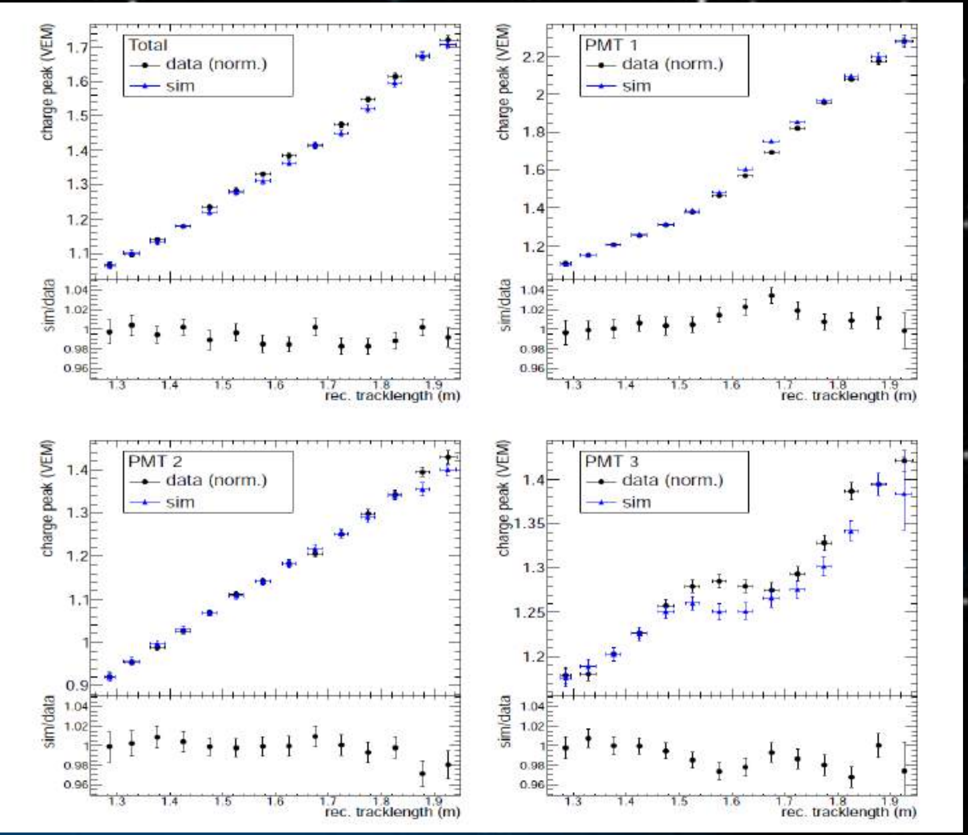
Conclusions II

- Auger is completing a comprehensive picture of the astrophysical sources of the UHECR
  - Needs SD (high stats) mass sensitive parameters to asses the mass at the highest energies, and to separate primaries (Charged Particle Astronomy)
- High Energy Hadronic Models do not describe well data above the 100 TeV scale.
  - Existence of new phenomena or
  - Simply fine tunning
- Auger Upgrades and enhancements: increase the sensitivity to the different shower components to attack and possibly close the above questions:
  - AugerPrime
  - AMIGA
  - Radio
  - MARTA EA

Back up

Validation of tank simulations with a Muon Telescope

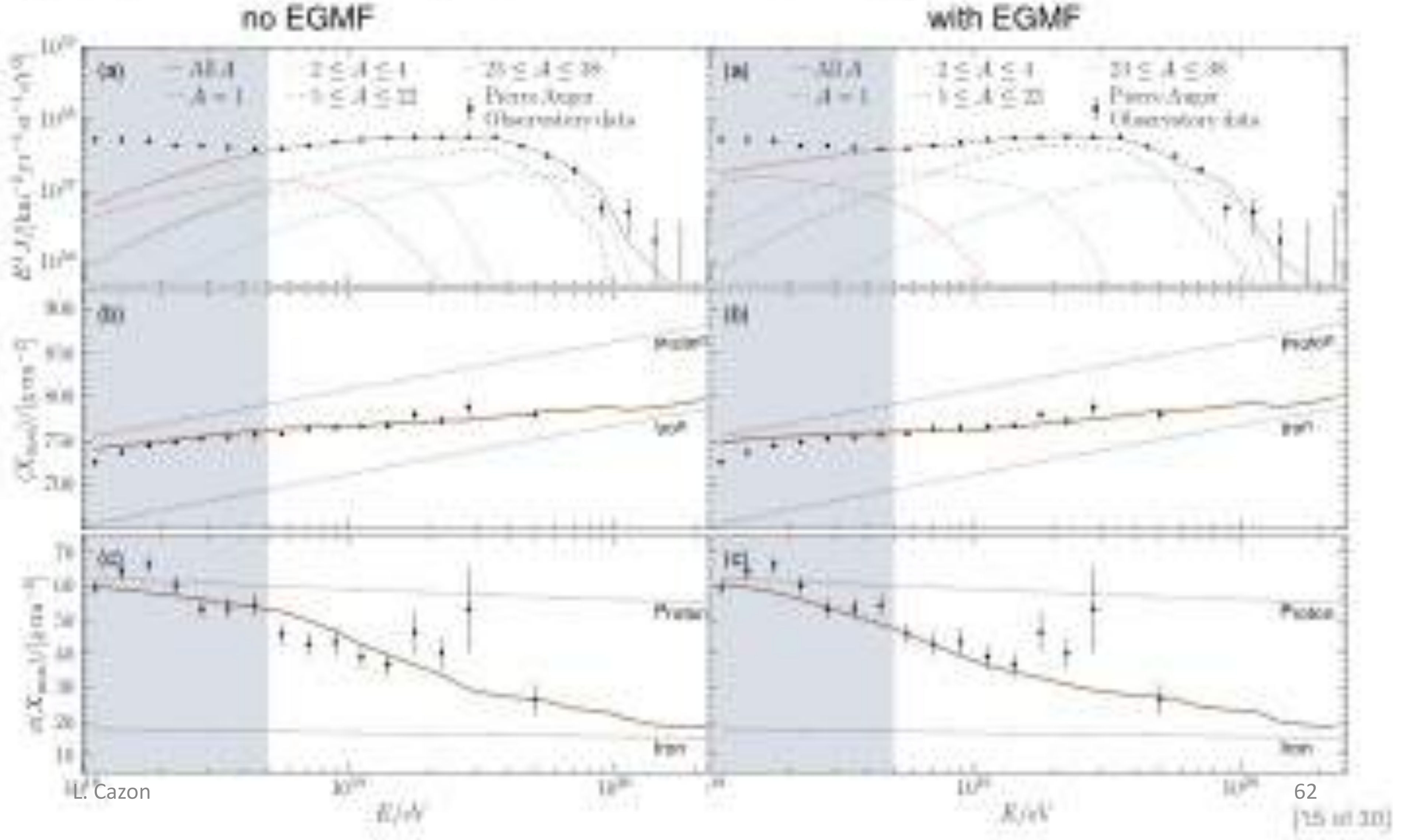




Two segmented RPCs above and beneath the Gianni-Navarra tank reveal a good match between tank simulations and measurents (signal vs tracklengh)

Combined Fit of Spectrum and X_{max} Distributions

rigidity-dependent cutoff at source: $E_{max} = R_{cut}\,Z$, power law injection $E^{-\gamma}$, propagation with CRPropa3, Gilmore12 EBL, Dolag12 LSS



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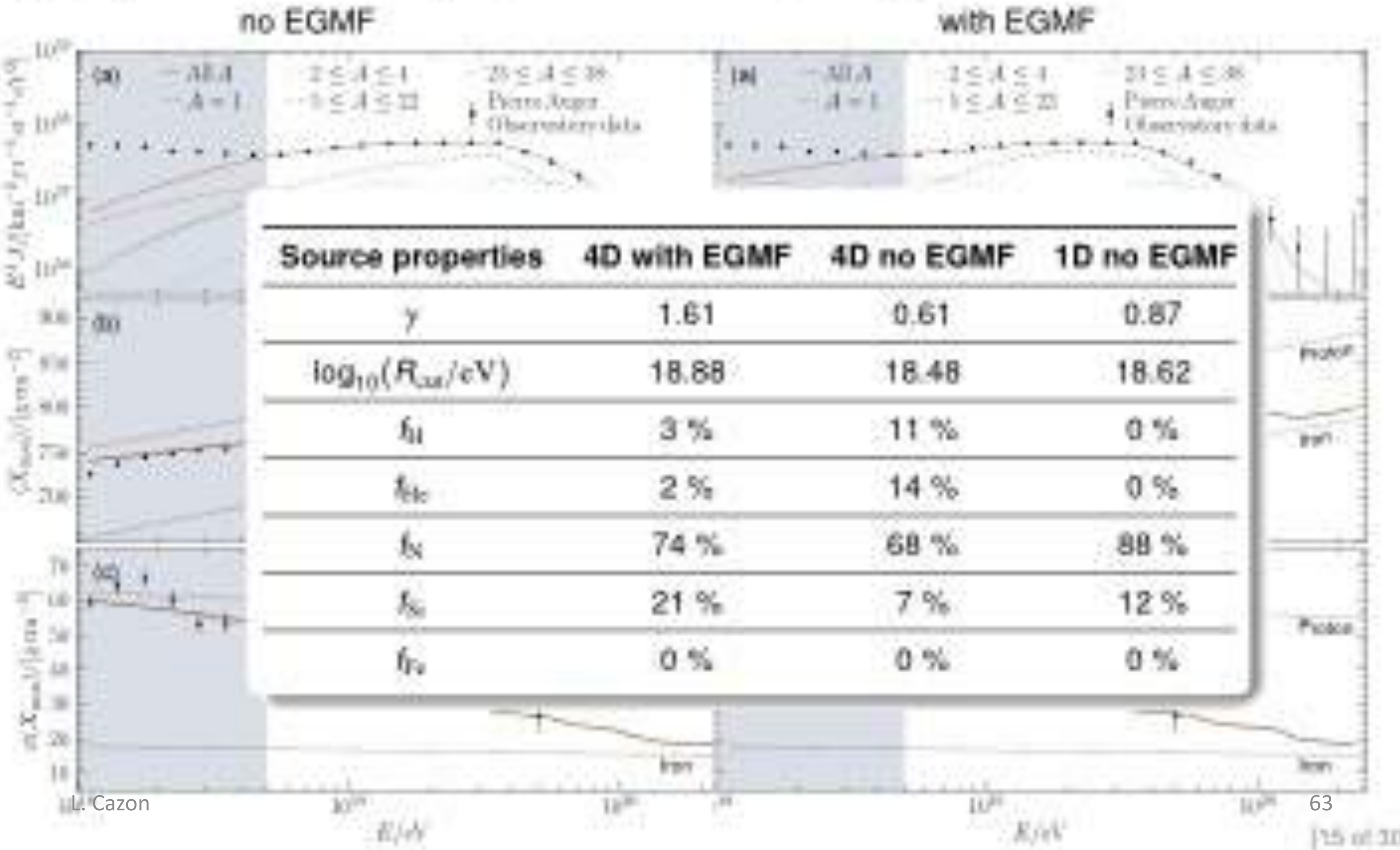

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