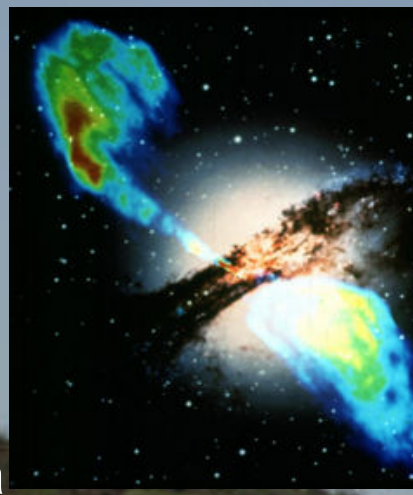
Ultrahigh Energy Cosmic Rays with the Pierre Auger Observatory

Ad M. van den Berg
Kernfysisch Versneller Instituut
University of Groningen

Pierre Auger Collaboration

- **Its mission:**
  - Study of ultra-high energy **cosmic rays**; the most energetic particles in the Universe
- **Its tools:**
  - Its observatory in Argentina of 3000 km^2 taking data since 2004
- **Its people:**
  - More than 400 scientists from 18 countries
- **Its results**
  - Many papers and PhDs



But 1st, Jan's 65th !

Sonnenborgh Utrecht 1974-1978

Sonnenborgh Utrecht 1974-1978

CAN April 2004

Astroparticle Physics Key Issues

Jan Kuijpers

Dep. of Astrophysics/ HEFIN
University of Nijmegen

CAN April 2004 Jan & Gerard

Key questions in astroparticle physics:

- ORIGINS CRs (HADRONS+LEPTONS):
  SNRs, BHs, NSs, DARK MATTER, DARK ENERGY
- UNIVERSAL ACCELERATION PROCESS?
- TeV GAMMA RAYS FROM ELECTRONS OR PROTONS?
- ORIGIN $e^{\pm}$ PLASMA?
- ORIGIN OF MAGNETIC FIELD?
- ENERGY PARTITIONING
- IS THERE A HIGH ENERGY CR CUT-OFF?
- QUEST FOR HIGHEST ENERGY CRs AND SOURCES

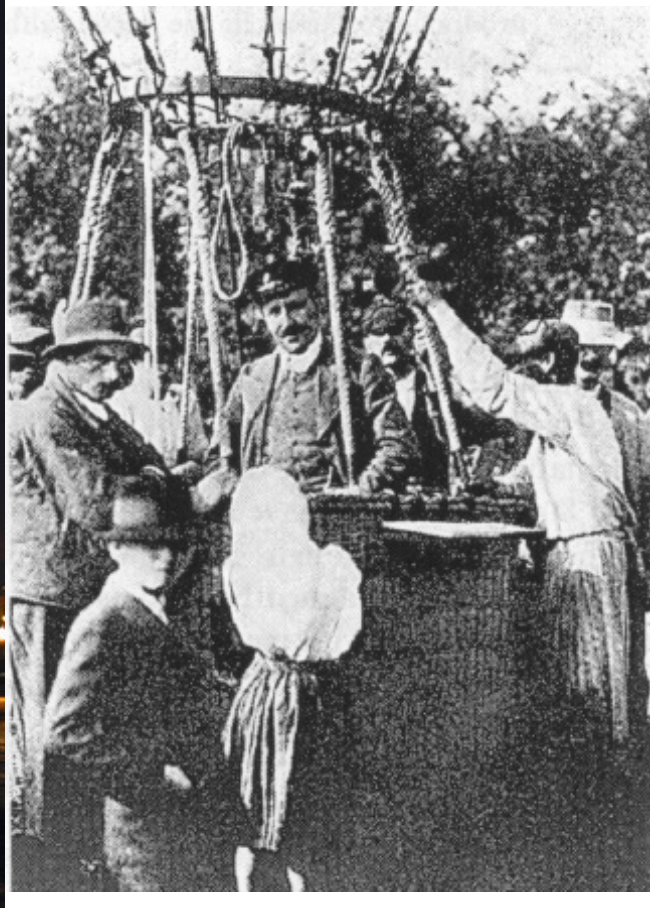
PIERRE AUGER OBSERVATORY

2 communities astroparticle detectors
LOFAR + ANTARES

PIERRE AUGER OBSERVATORY

260404 Astroparticle Physics 19

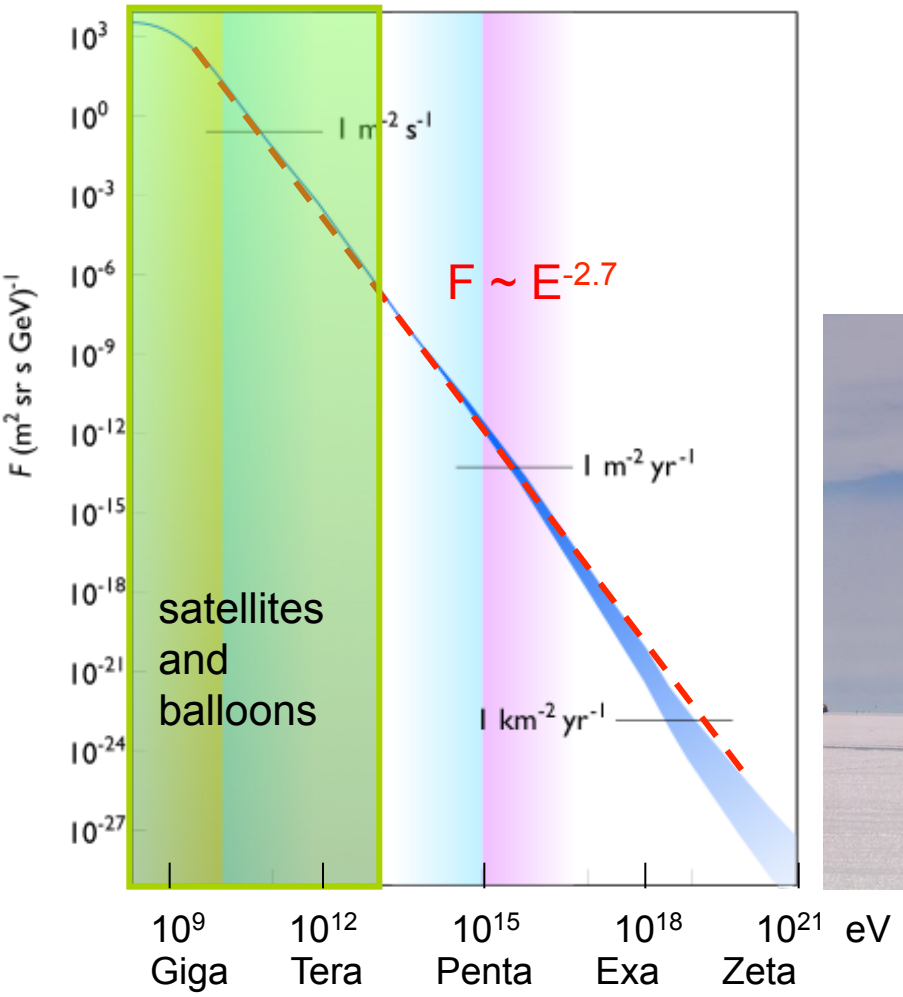
Theodor Wulf & Victor Hess

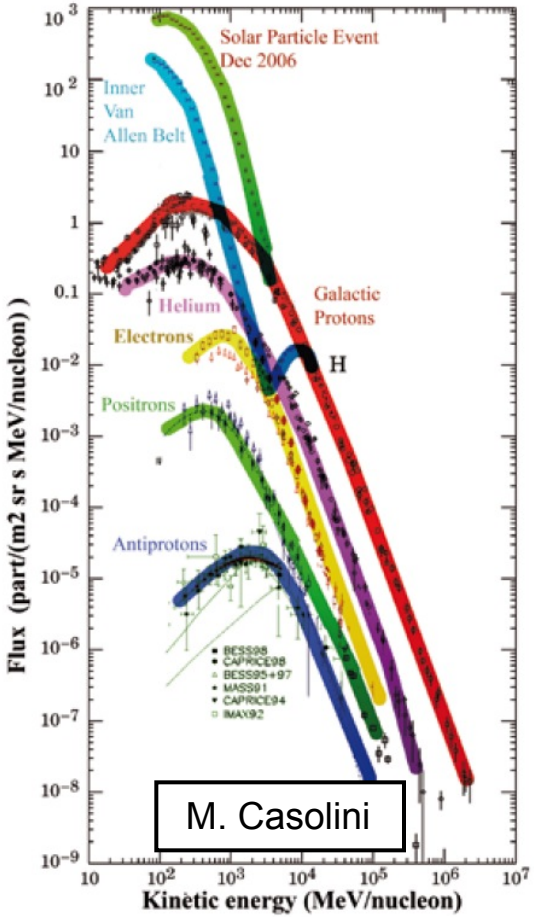


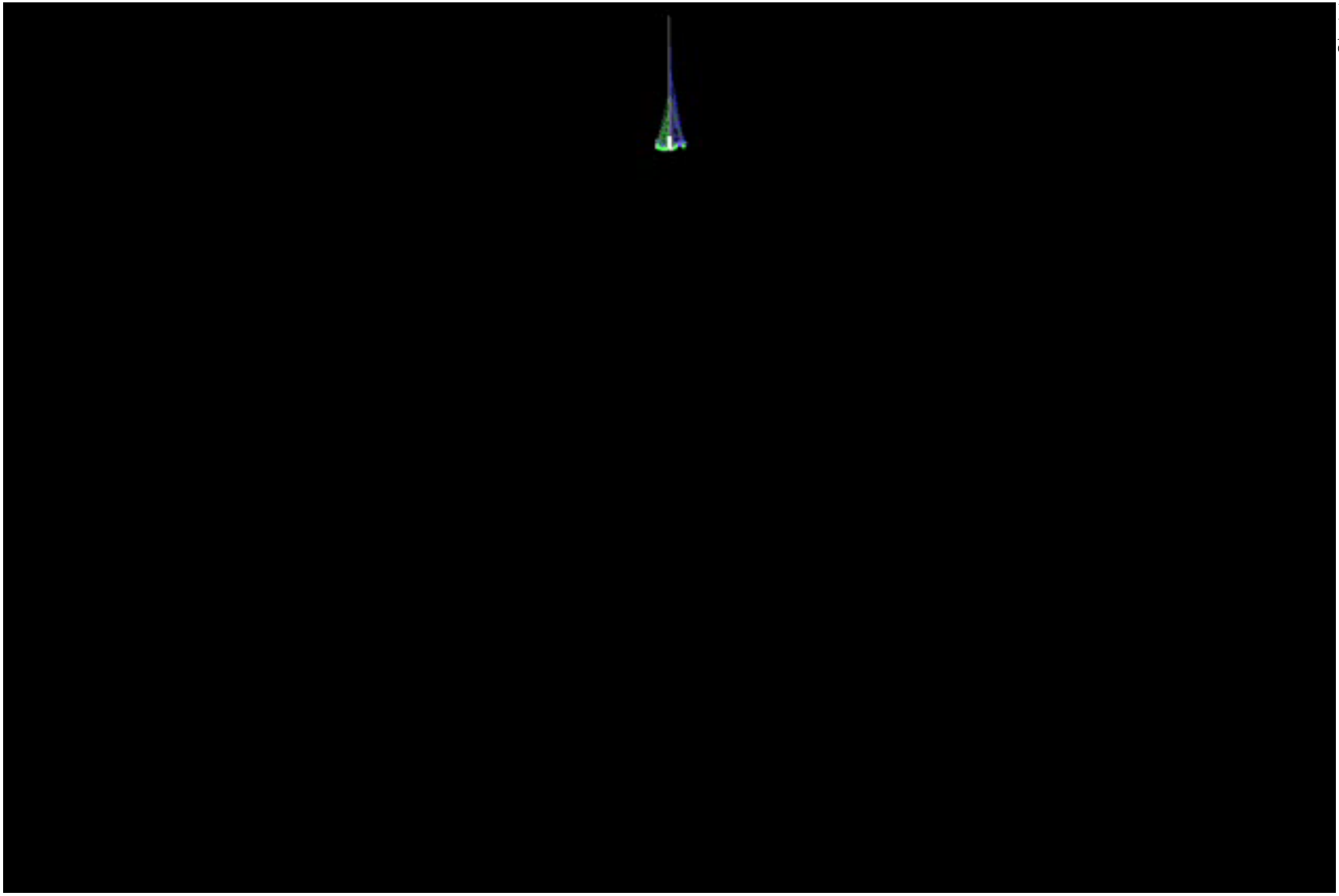
Particles from the cosmos

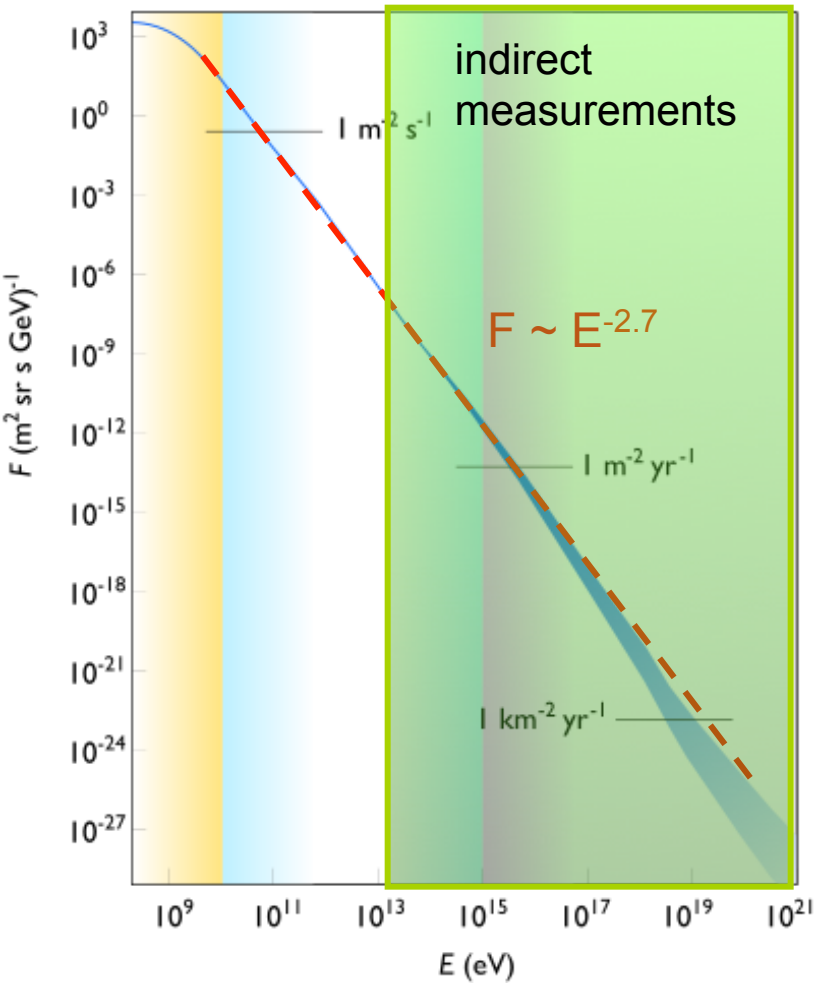
- The outer layers of the atmosphere are continuously bombarded by cosmic particles
- The flux spectrum shows a rather featureless behavior with a few kinks
- Particles at the highest energy are very rare (< 1 km^{-2} yr^{-1}) and their origin is a profound question in astrophysics
- Origin of the high(est) energy cosmic rays = BIQ QUESTION !

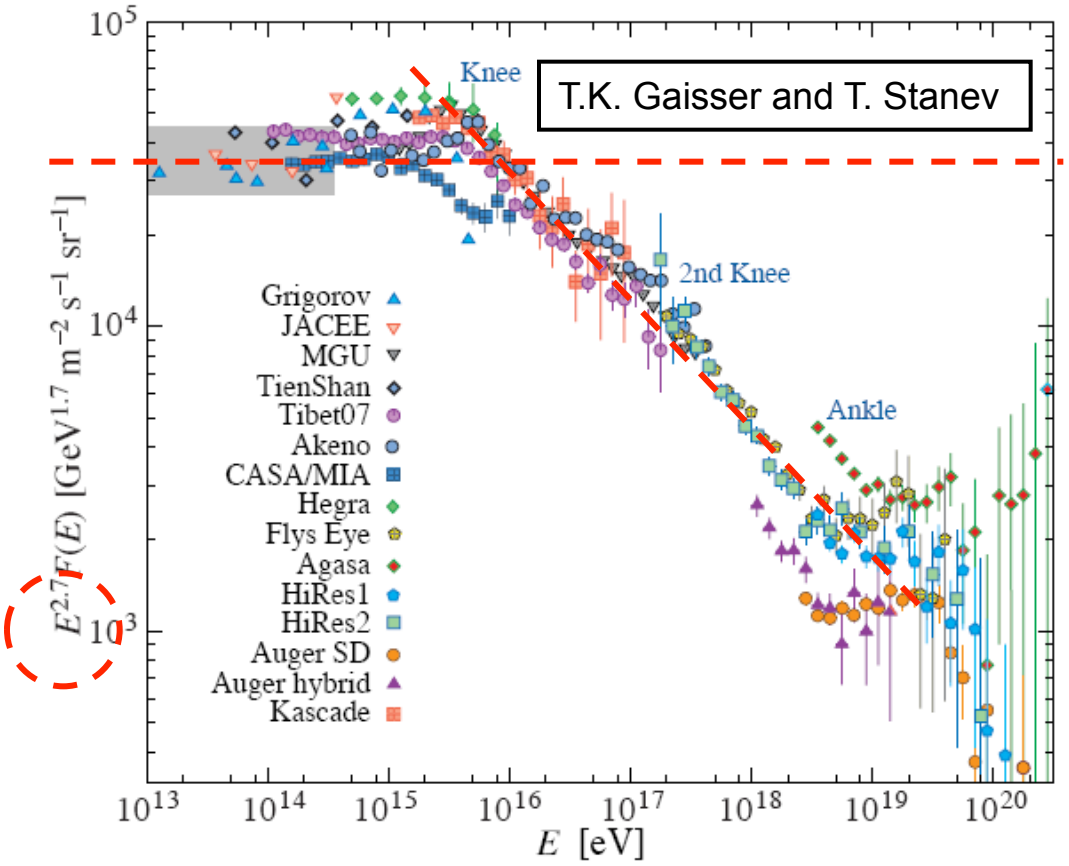
The cosmic-ray flux spectrum

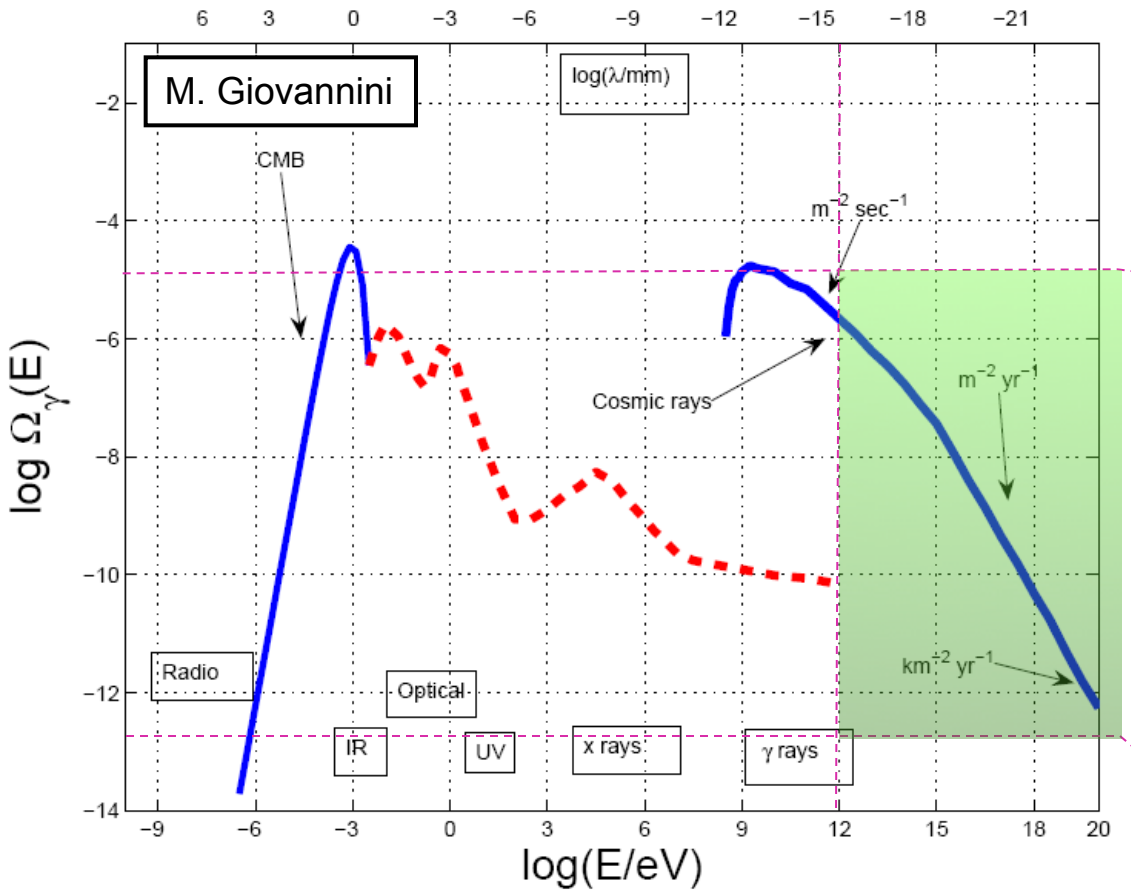




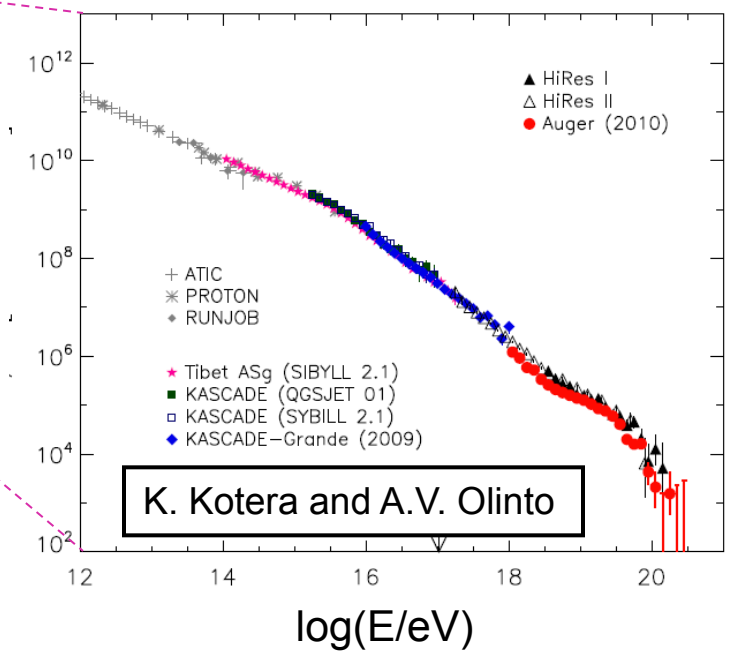



indirect measurements
1 m^{-2} s^{-1}
F ~ E$^{-2.7}$
1 m^{-2} yr^{-1}
1 km^{-2} yr^{-1}
F (m^2 sr s GeV)$^{-1}$
E (eV)


T.K. Gaisser and T. Stanev
Knee
2nd Knee
Ankle
Grigorov
JACEE
MGU
TienShan
Tibet07
Akeno
CASA/MIA
Hegra
Flys Eye
Agasa
HiRes1
HiRes2
Auger SD
Auger hybrid
Kascade
$E^{2.7}F(E)$ [GeV$^{1.7}$ m^{-2} s^{-1} sr^{-1}]
E [eV]



log[E^{2}dN/dE (eV m^{-2} s^{-1} sr^{-1})]



Energy content

- The energy density of cosmic rays is ~1 eV/cm^3 = 10^{-12} erg cm^{-3}
- Thus for cosmic rays: $\rho_E = 10^{-12}$ erg cm^{-3}

Again let's compare with some other astrophysical energies:

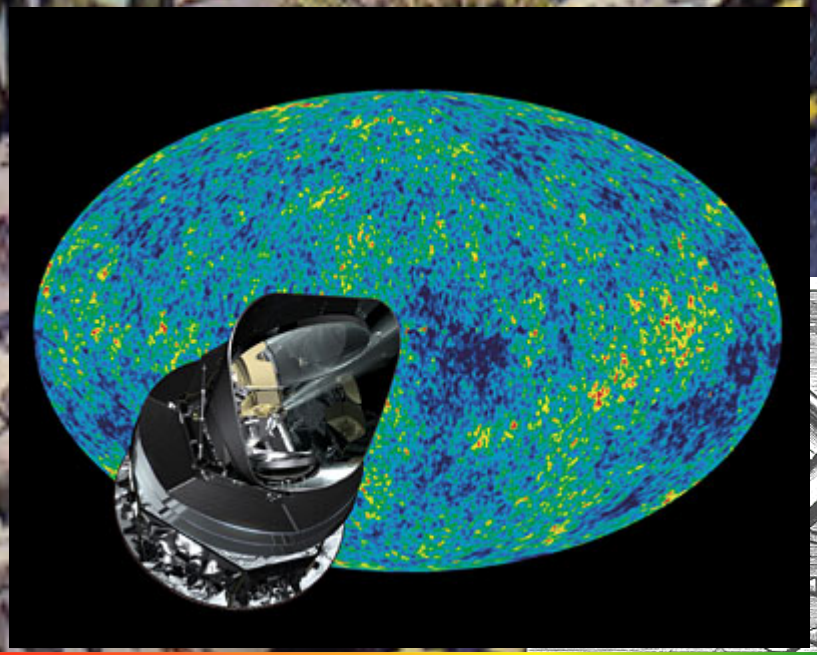
CMB density:	~1 eV cm^{-3}
visible light density:	~1 eV cm^{-3}
Galactic magnetic field density: $B^2/(8\pi)$	~1 eV cm^{-3}

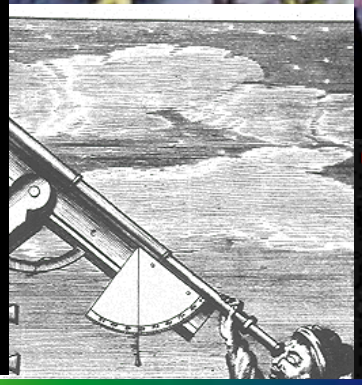
COSMIC RAYS HAVE AN APPRECIABLE ENERGY CONTENT

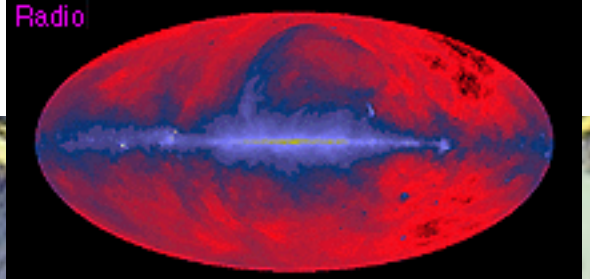
rijksuniversiteit groningen

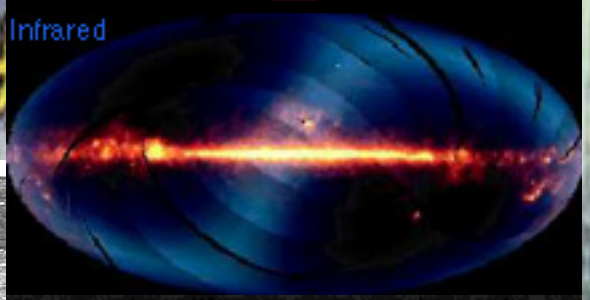
Kernfysisch Versneller Instituut

PIERRE AUGER OBSERVATORY

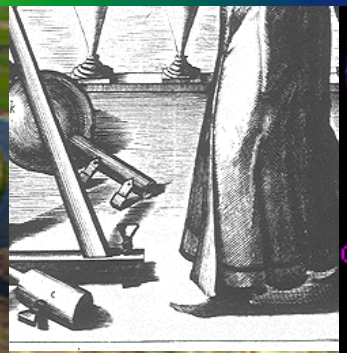


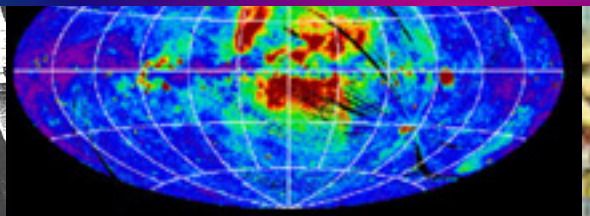


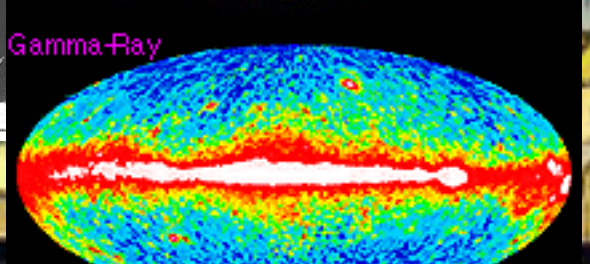




ELECTROMAGNETIC RADIATION

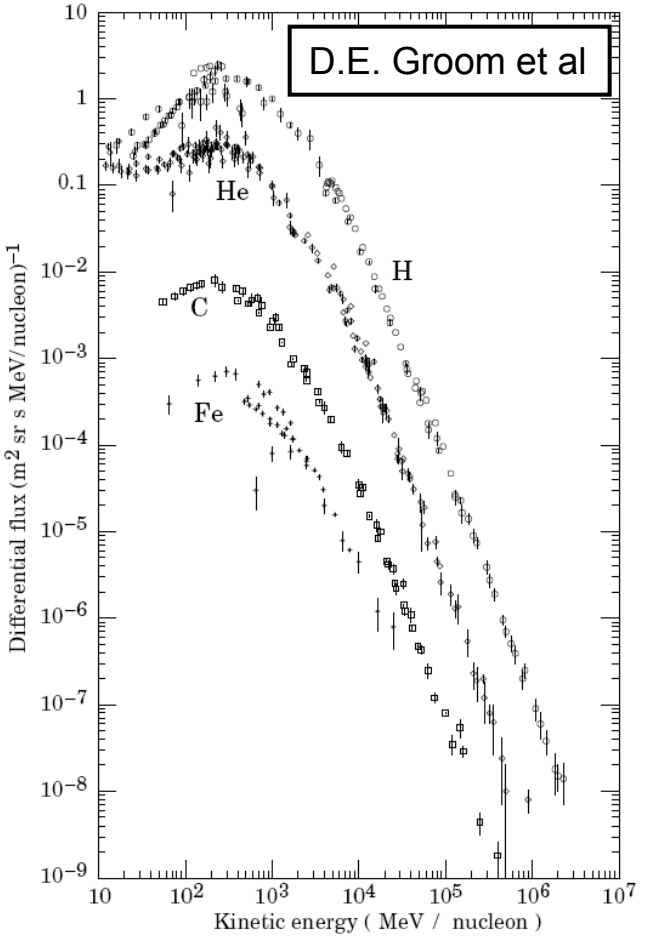






Cosmic rays are particles!

- They have
  - mass and charge
- There are magnetic fields in the cosmos (earth, sun, Milky-way and beyond)
  - charged particles are bent by these fields



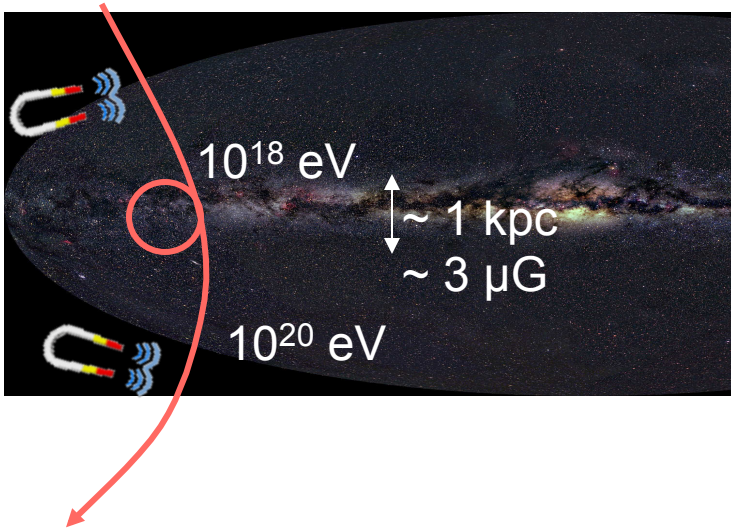
Magnetic fields

- These charged particles obey the laws of Nature:

$$\mathbf{F} = q\,[\mathbf{E} + \mathbf{v} \times \mathbf{B}]$$

- Magnetic confinement Larmor radius: (R_L B = p/q)

$$R_L \approx 100 \text{ kpc } [\, E / (10^{20} \text{ eV } q) \,]\, [\, \mu G / B]$$



Particles & Fields

- Charged particles in the cosmos are bent; therefore their point of origin might be difficult to identify (amount of bending depends on momentum and charge: p/q)

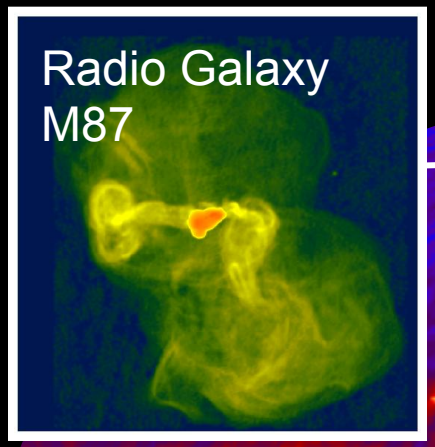
PARTICLE ASTRONOMY depends on detailed knowledge of B

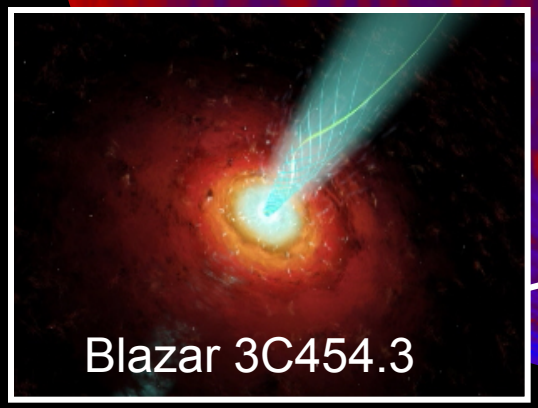
- Charged particles can be trapped in magnetic fields or they can bounce from “magnetic clouds” (Fermi)
- The trapping can only happen up to certain energies (or more precise: up to a certain ratio of momentum and charge: p/q)

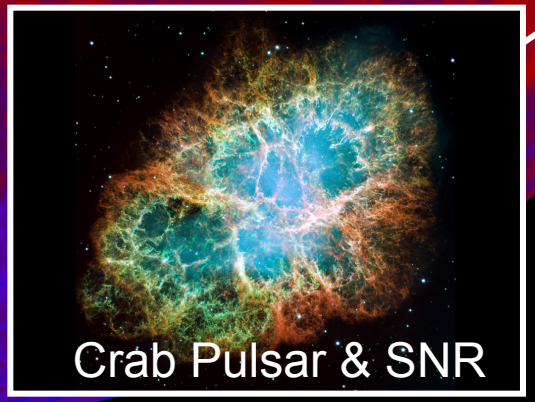
ACCELERATION OF CHARGED PARTICLES


But to begin with ... SN1054

High-energy Universe



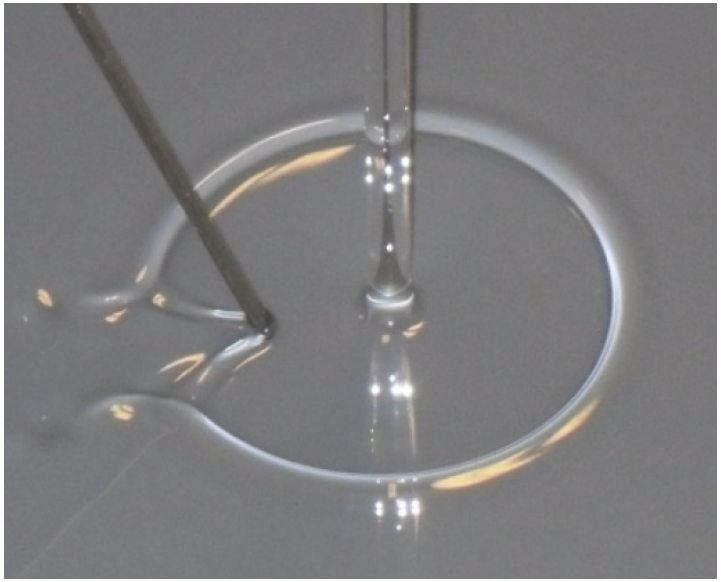


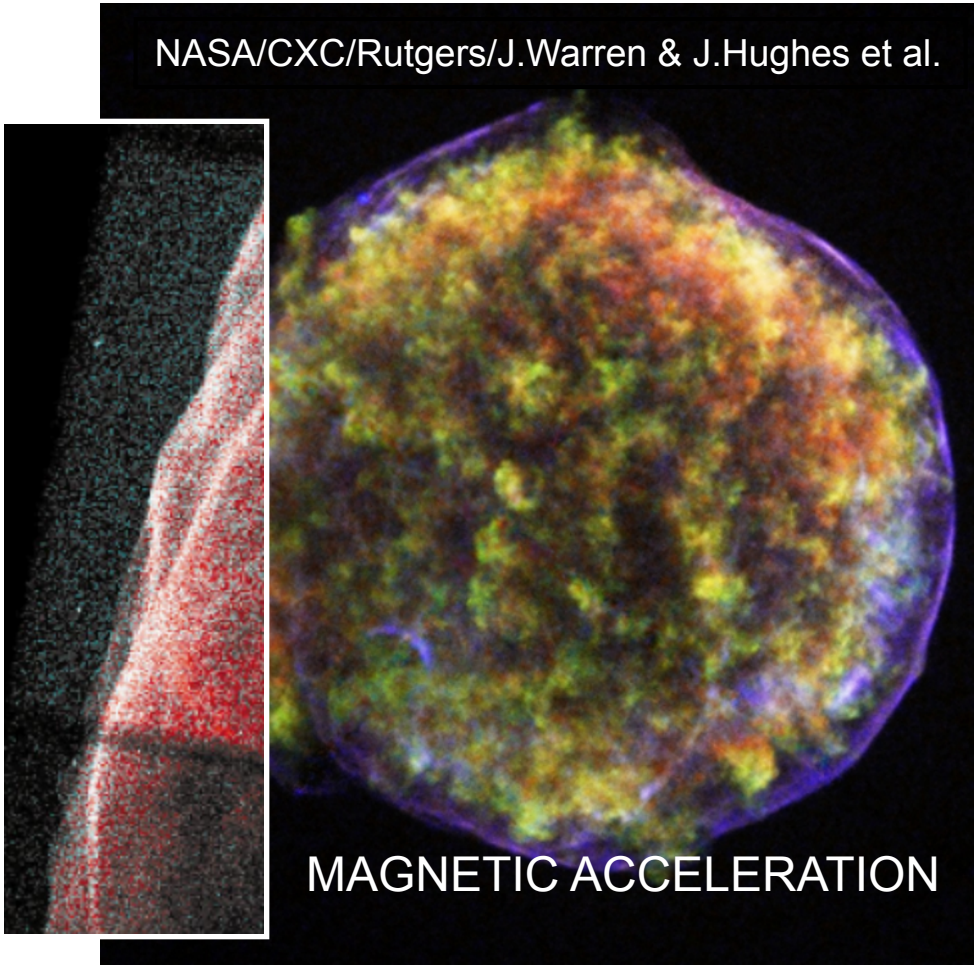


EGRET (part of CGRO) gamma-ray sky map > 100 MeV

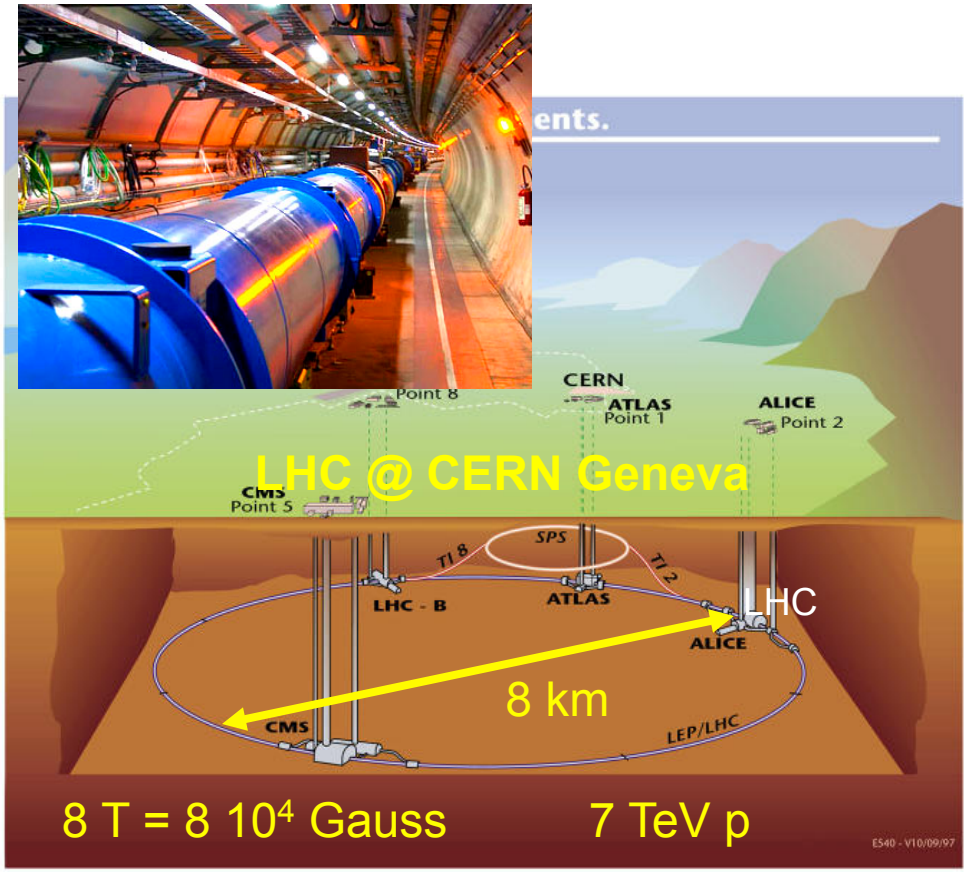
Cosmic accelerators

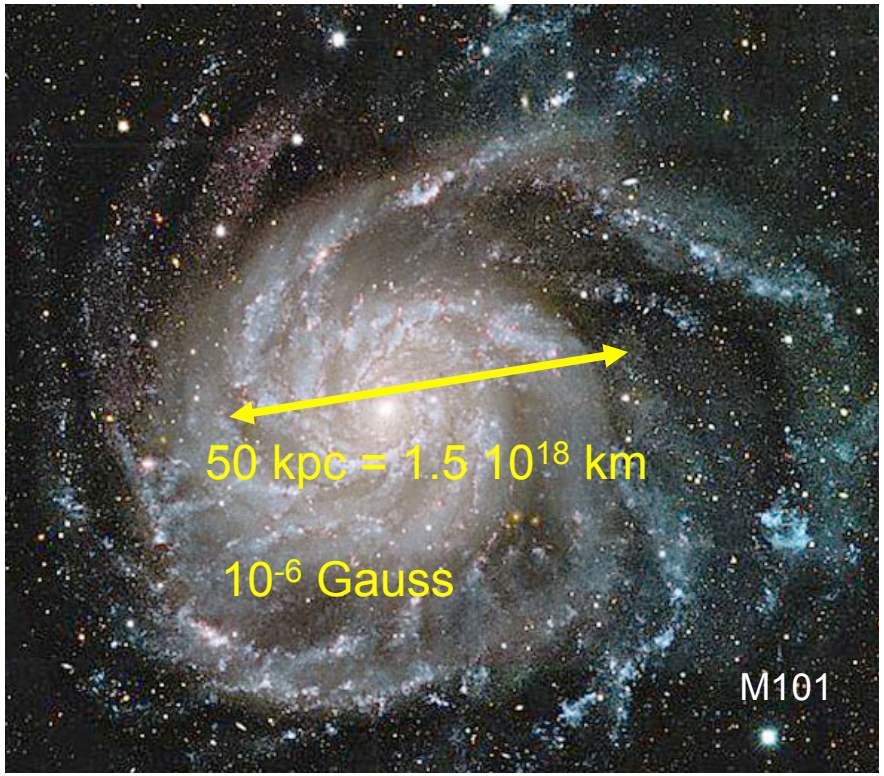
- SN1572
  - Chandra X-ray image
  - blue: electrons
  - red / green: gas

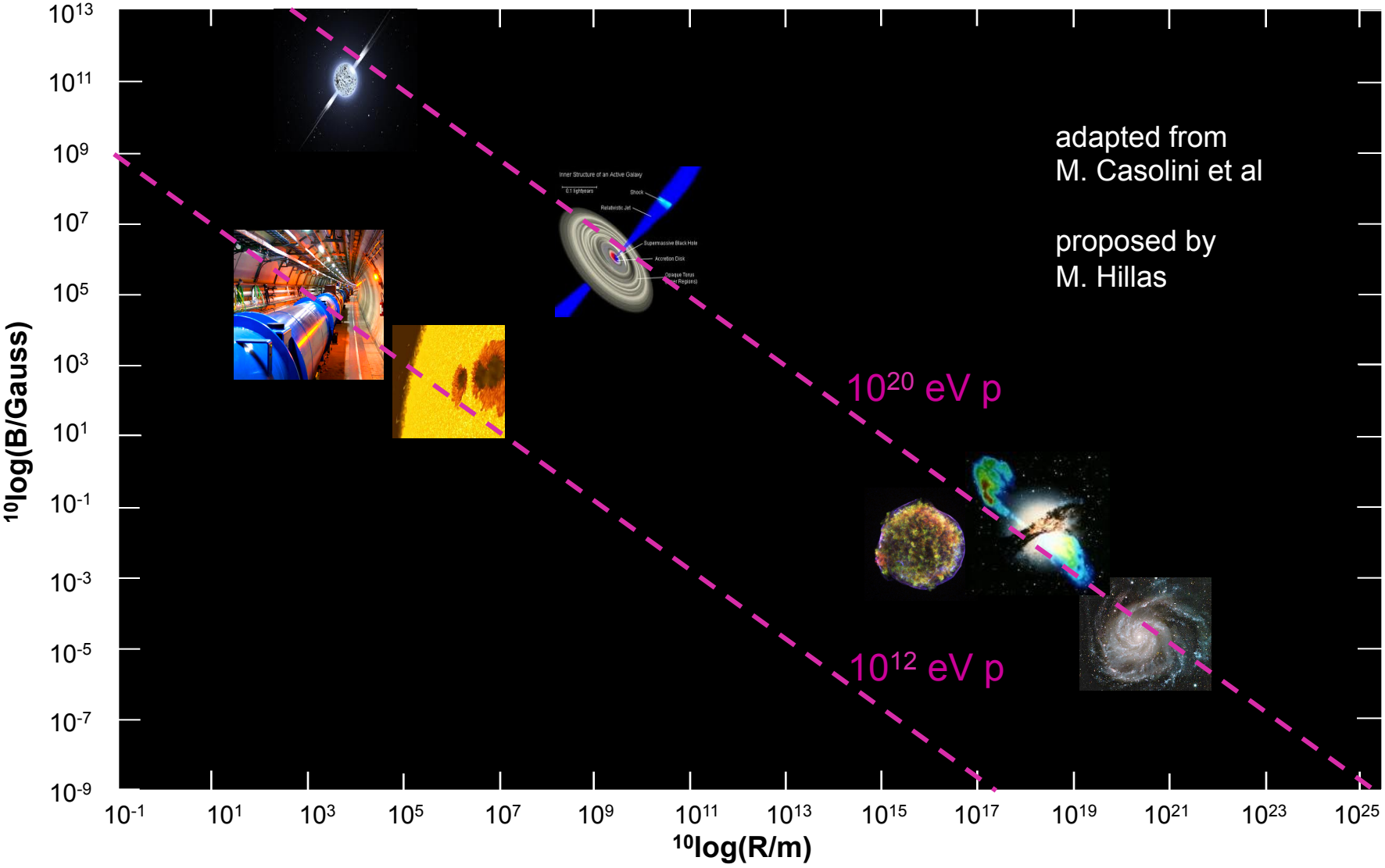




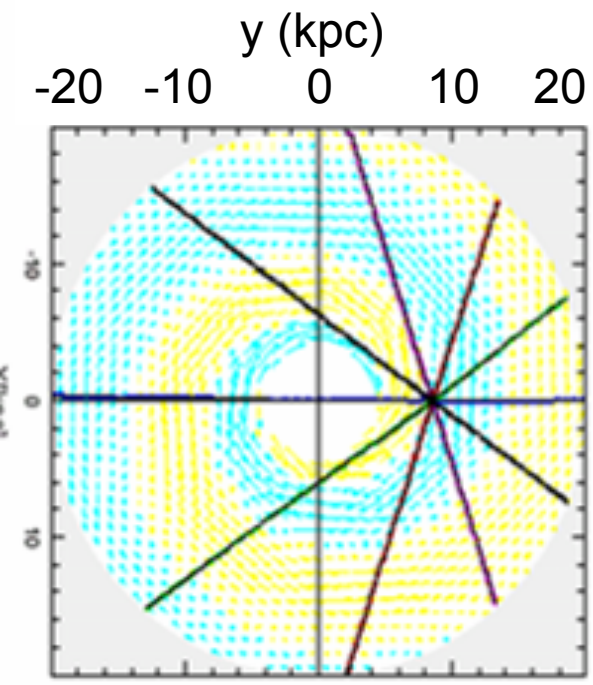
Accelerators



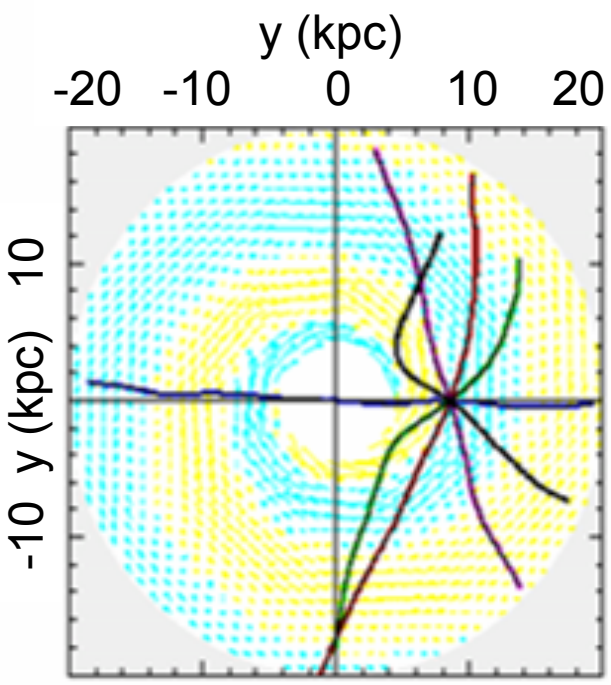



adapted from
M. Casolini et al
proposed by
M. Hillas
10^{20} eV p
10^{12} eV p
^{10}log(B/Gauss)
^{10}log(R/m)
10^{13}
10^{11}
10^{9}
10^{7}
10^{5}
10^{3}
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-1} 10^{1} 10^{3} 10^{5} 10^{7} 10^{9} 10^{11} 10^{13} 10^{15} 10^{17} 10^{19} 10^{21} 10^{23} 10^{25}

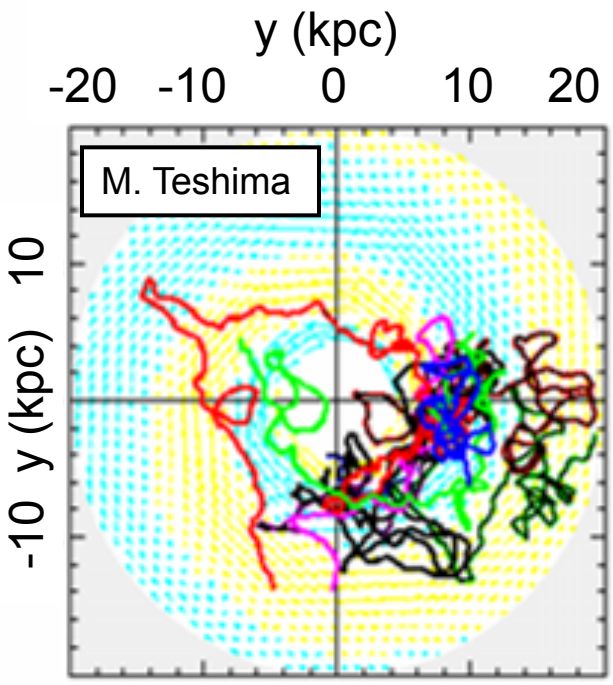
Paths through the Galaxy



10^{20} eV



10^{19} eV

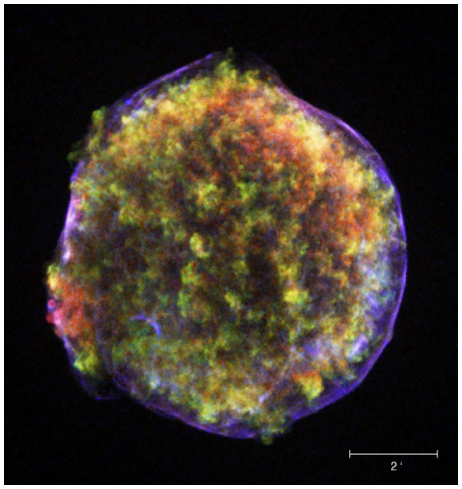


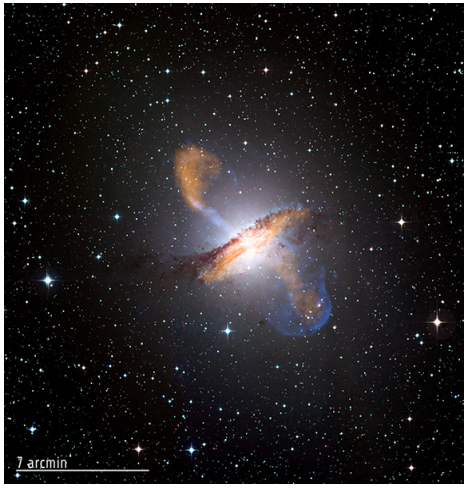
10^{18} eV

$$\delta \cong 16^{\circ} \frac{20\ \mathrm{EeV}}{\mathrm{E/Z}} \int_0^L \frac{dl}{3\ \mathrm{kpc}} \frac{B}{2\ \mu\mathrm{G}}$$

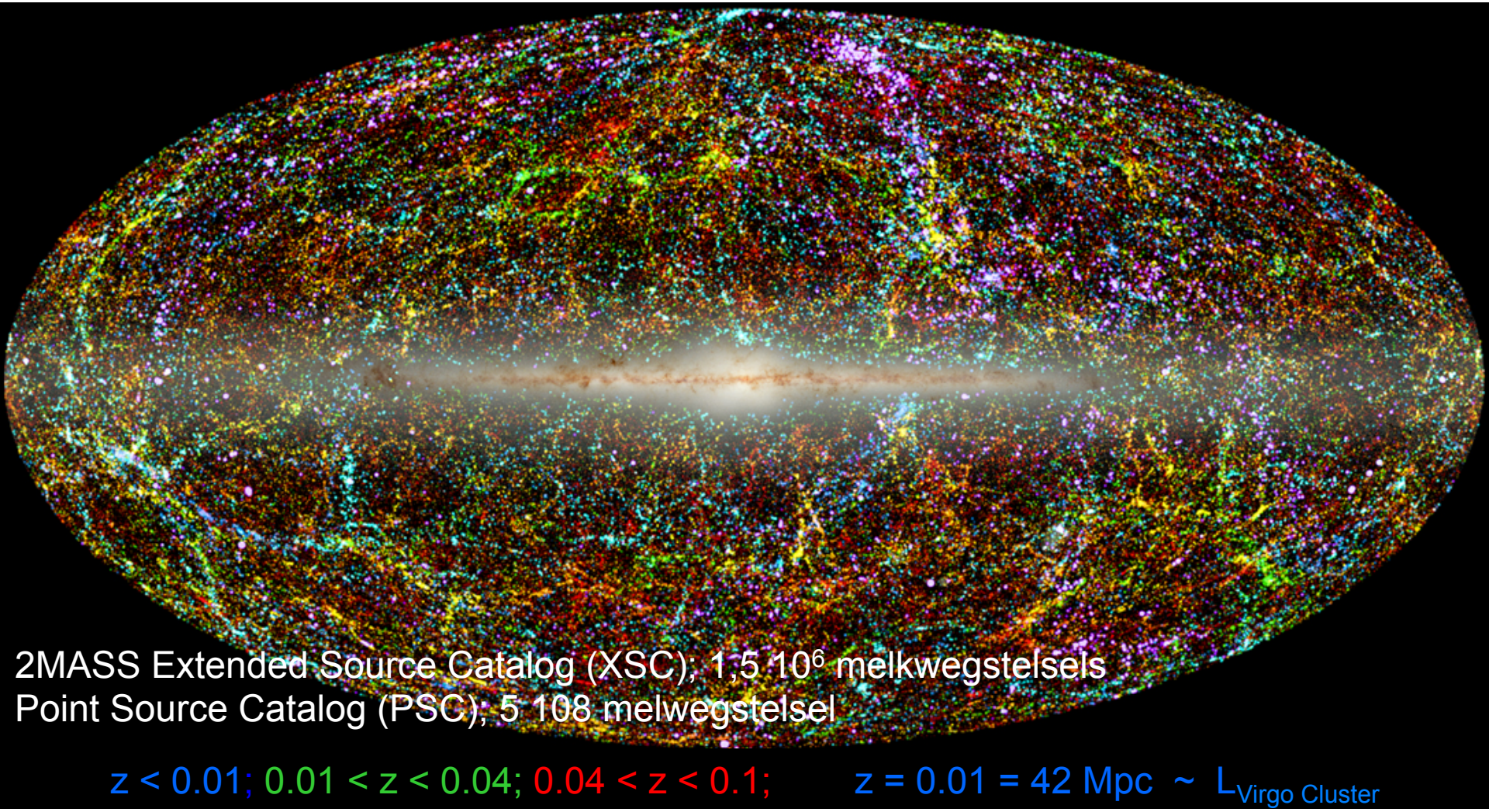
The sources

- Galactic cosmic rays are contained in the Galaxy by its magnetic field from which they may escape eventually
- Using arguments based on energy content, …… up to 10^{17} eV, most likely supernovas are the sources
- And beyond that energy ?????

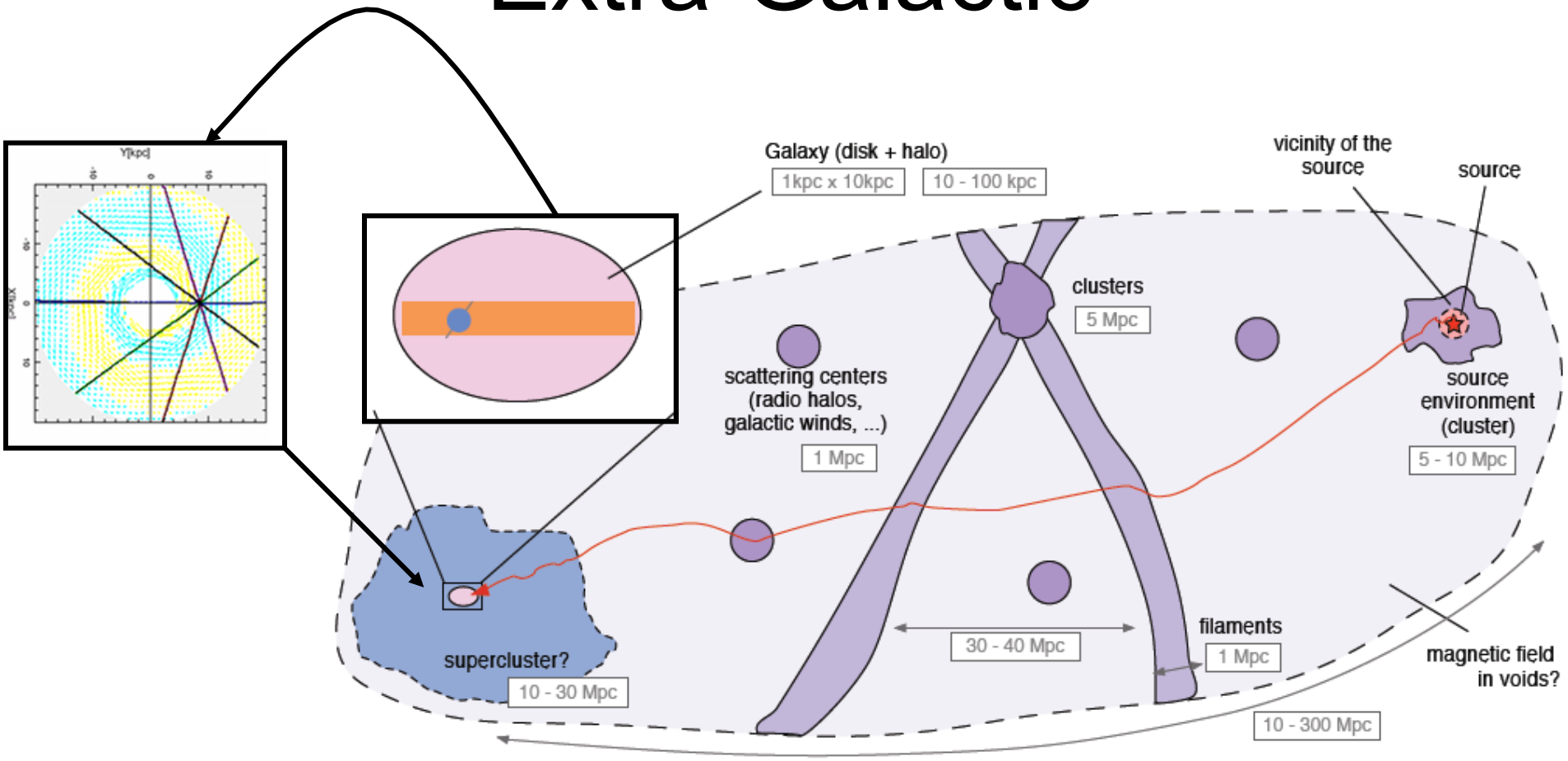




Mass in the local Universe



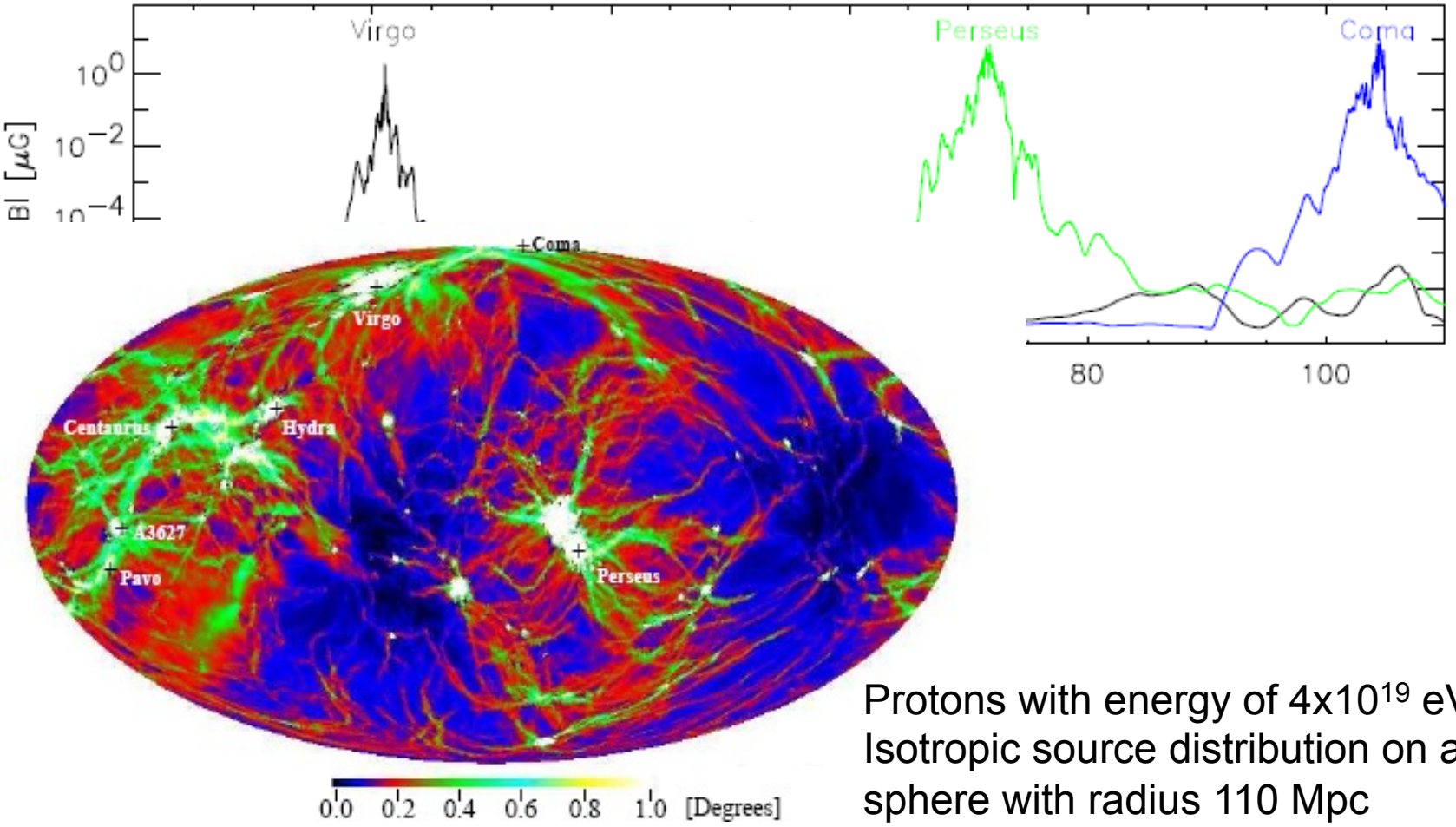
Extra-Galactic



K. Kotera and A.V. Olinto

Extragalactic fields

K. Dolag et al

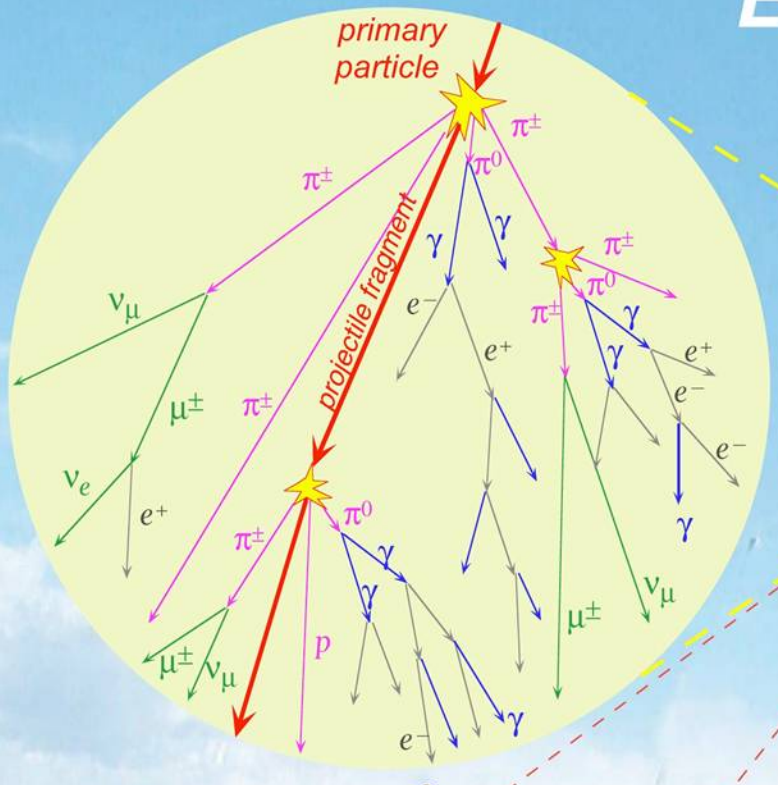


Protons with energy of 4×10^{19} eV
Isotropic source distribution on a sphere with radius 110 Mpc

Summarizing

- The flux of cosmic rays with $E > 10^{19}$ eV is very small: 1 km^{-2} yr^{-1} sr^{-1}
- Cosmic rays up to 10^{17} eV are most likely produced in our Galaxy from and accelerated by Supernova Remnants
- At energies $E > 10^{20}$ eV cosmic rays are not fully randomized in the arrival direction by magnetic fields
- If we want to find the sources at the highest energies, there might be a chance if we know
  - arrival direction, energy, and composition (mass or charge)

Extended Air Showers



primary particle

Pierre Auger Observatory:
10^{19} eV < E < 10^{21++} eV

Fluorescence light - isotropic

Trajektorie

Cherenkov light

$v \approx c$

1 m thickness

Electronic Schmidt telescope

Water-Cherenkov detectors

1,5 km


Argentina
Australia
Bolivia
Brasil
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Slovenia
Spain
United Kingdom
USA
Vietnam

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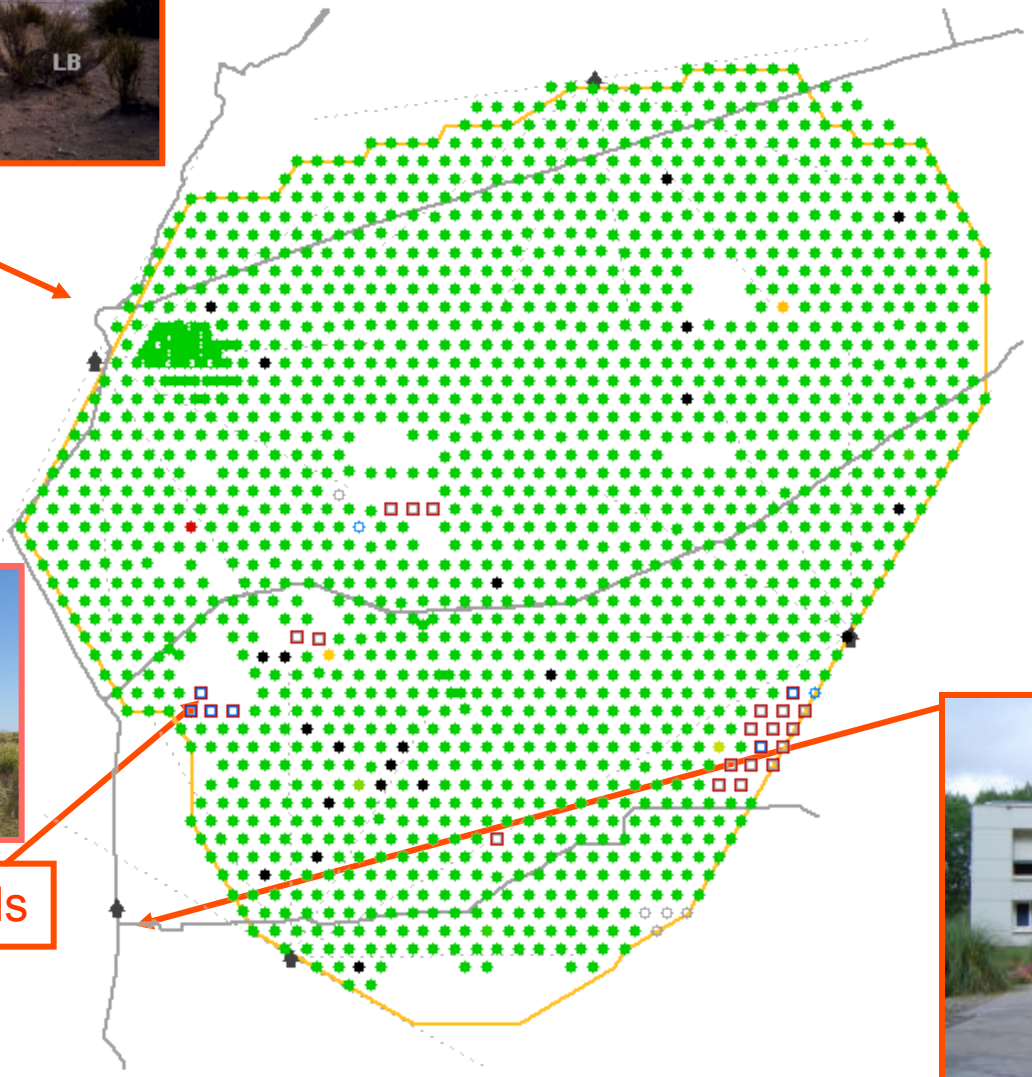
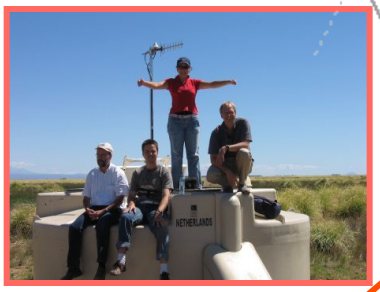
PIERRE AUGER OBSERVATORY

Uptime overview for Today





Netherlands

A footprint of 3,000 km^2

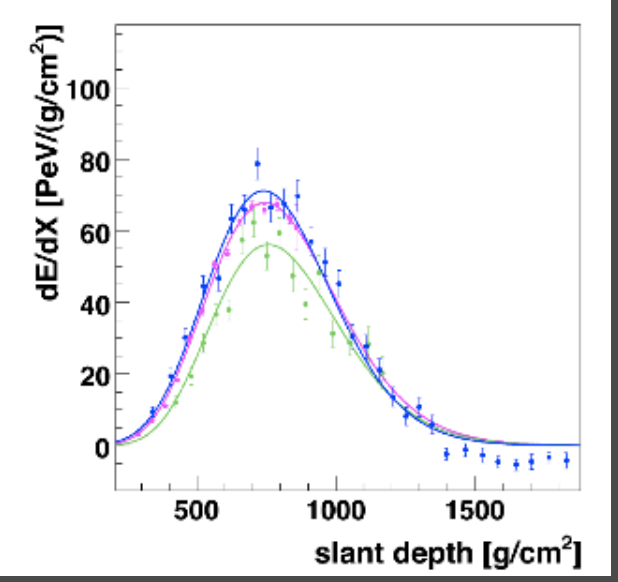
1660 Surface detectors

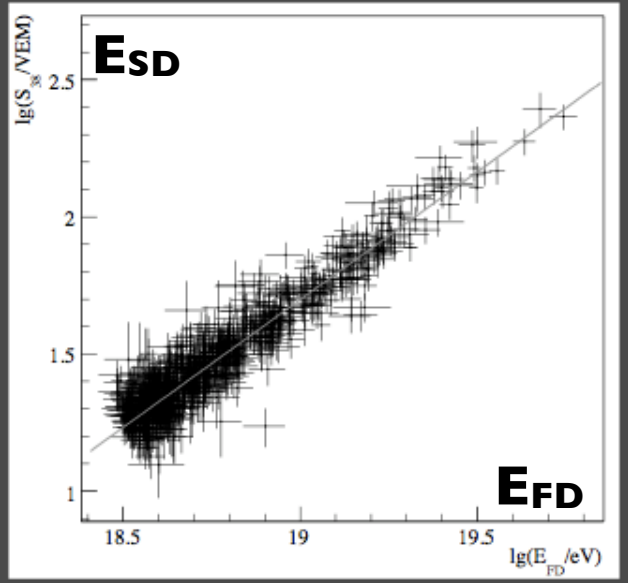
- Pulse height self-calibrating
- 100% duty cycle
- Acceptance easy to calculate
- Energy scale model dependent
- Only final stage of the shower is detected
- Partly sensitive to composition

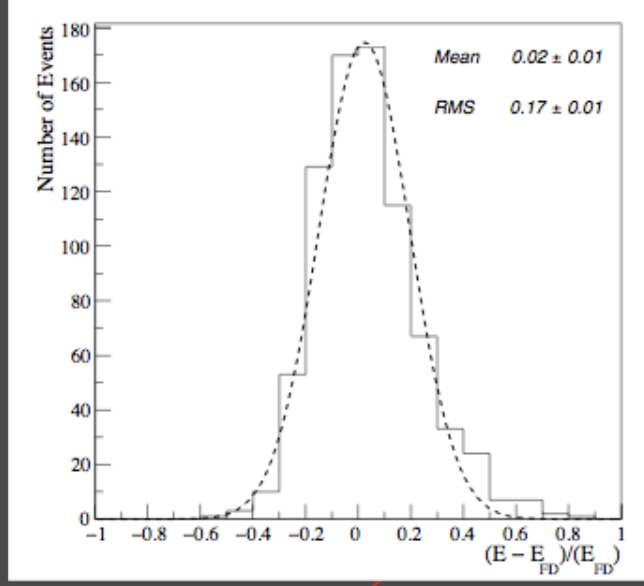
27 Air-fluorescence detectors

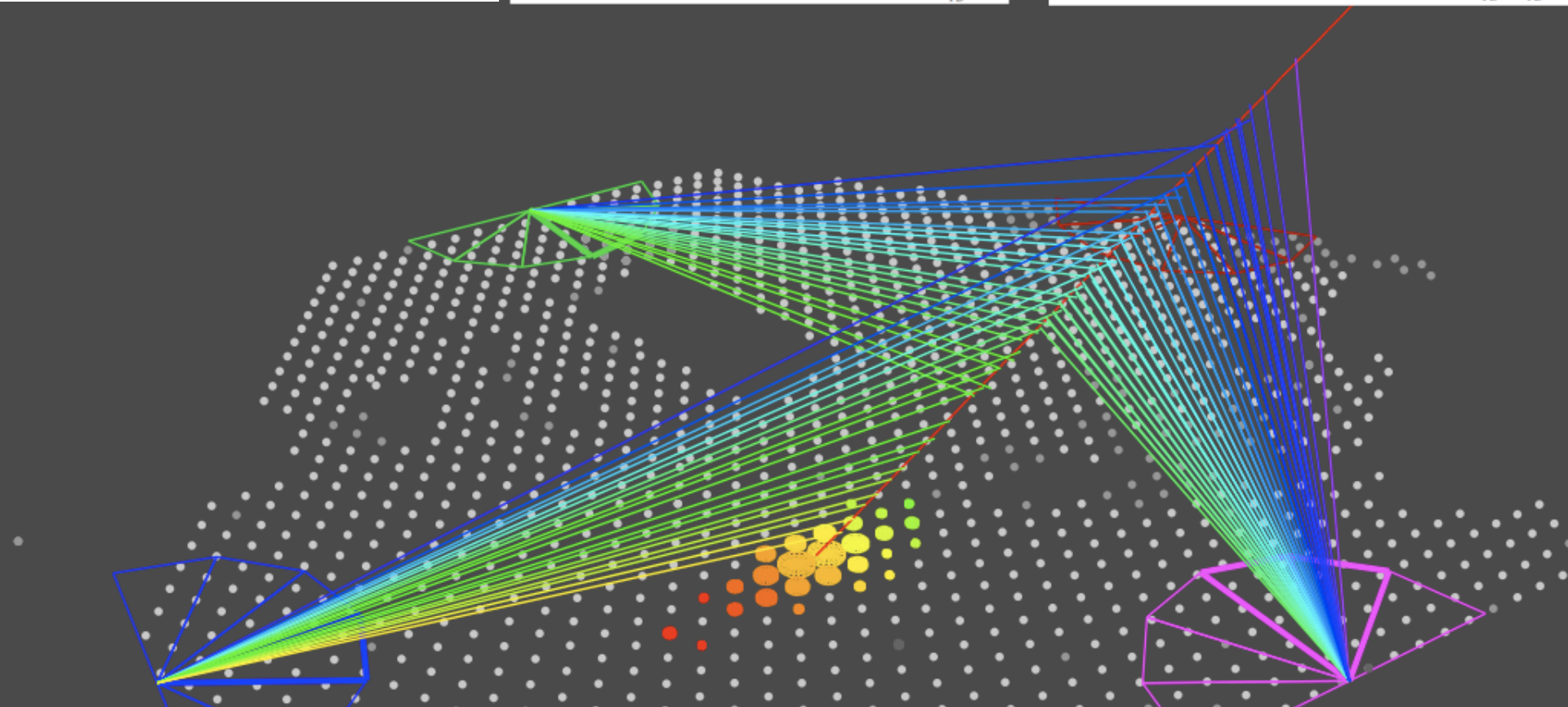
- Dedicated calibration procedures
- ≈10% duty cycle (dark nights)
- Acceptance depends on energy
- Precise and absolute energy determination
- Full shower tracking
- Sensitive to composition

Hybrid detection of air showers

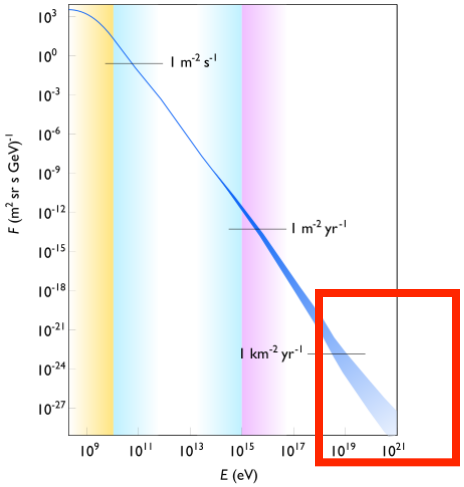

dE/dX [PeV/(g/cm²)]
slant depth [g/cm²]


E_SD
E_FD
lg(S38/VEM)
lg(E_FD/eV)

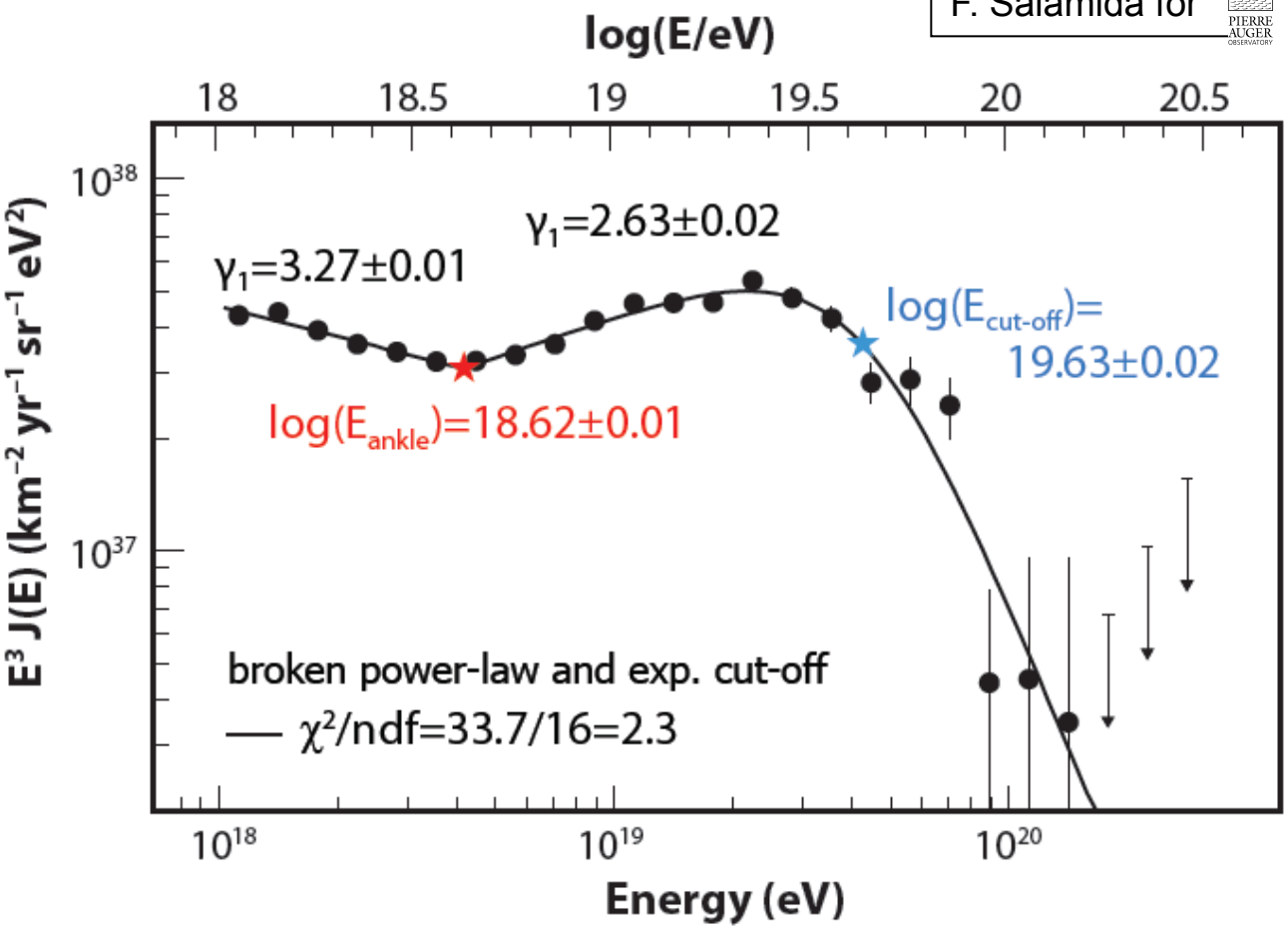

Mean 0.02 ± 0.01
RMS 0.17 ± 0.01
Number of Events
(E − E_FD)/(E_FD)

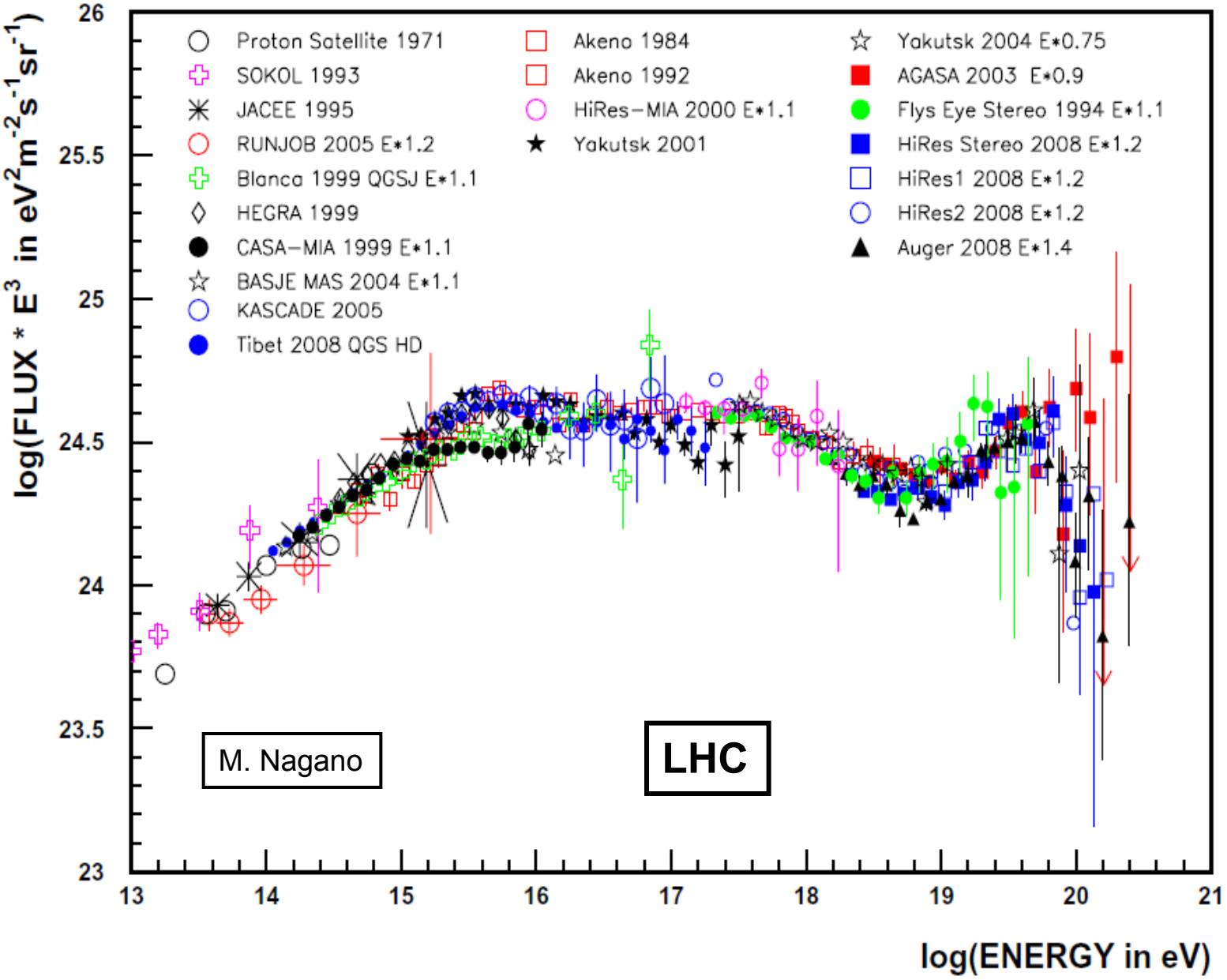


Limit on the flux spectrum?

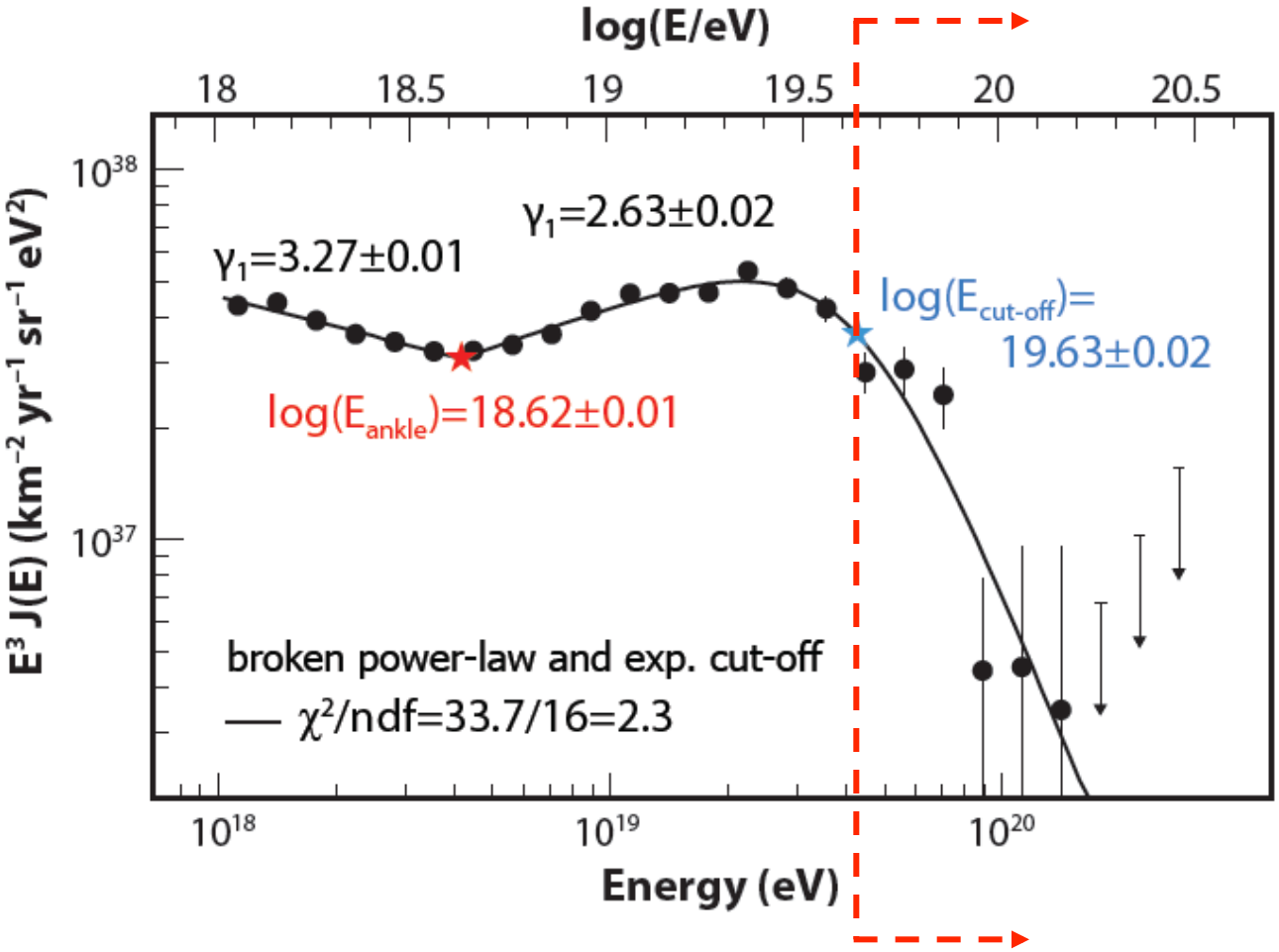


F. Salamida for PIERRE AUGER OBSERVATORY



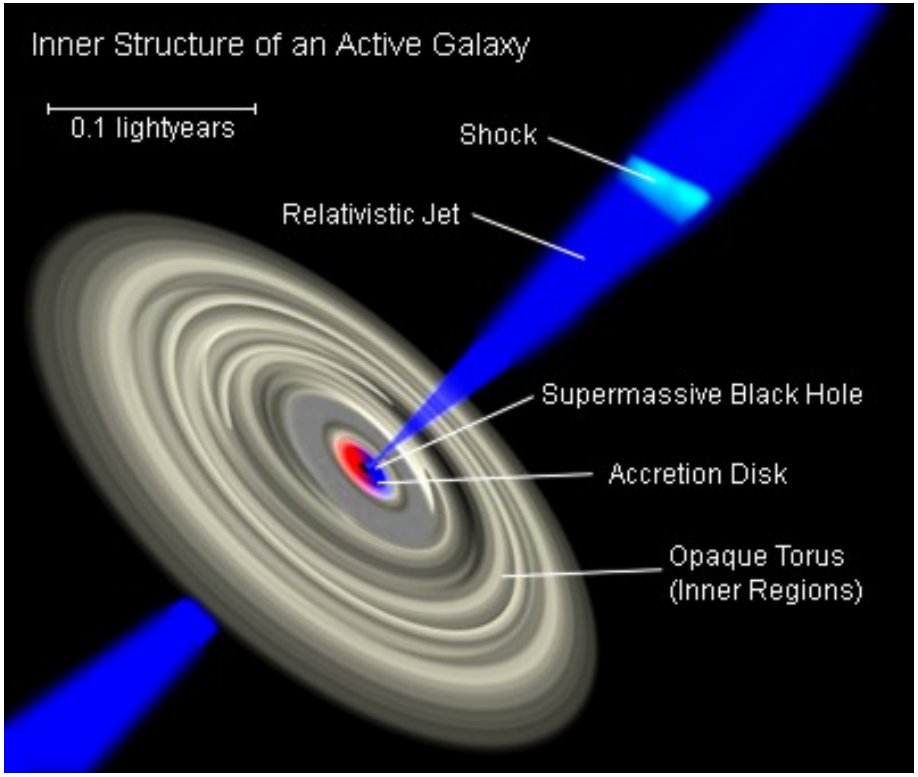

Proton Satellite 1971
SOKOL 1993
JACEE 1995
RUNJOB 2005 E*1.2
Blanca 1999 QGSJ E*1.1
HEGRA 1999
CASA–MIA 1999 E*1.1
BASJE MAS 2004 E*1.1
KASCADE 2005
Tibet 2008 QGS HD
Akeno 1984
Akeno 1992
HiRes–MIA 2000 E*1.1
Yakutsk 2001
Yakutsk 2004 E*0.75
AGASA 2003 E*0.9
Flys Eye Stereo 1994 E*1.1
HiRes Stereo 2008 E*1.2
HiRes1 2008 E*1.2
HiRes2 2008 E*1.2
Auger 2008 E*1.4
log(FLUX * E^3 in eV^2 m^-2 s^-1 sr^-1)
log(ENERGY in eV)
26
25.5
25
24.5
24
23.5
23
13
14
15
16
17
18
19
20
21
M. Nagano
LHC

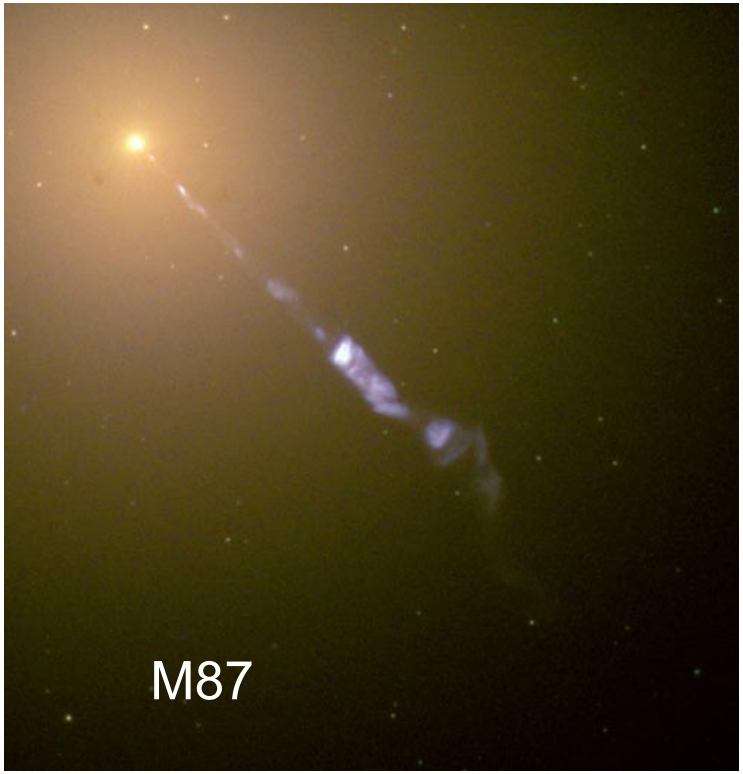
Can we trace back?



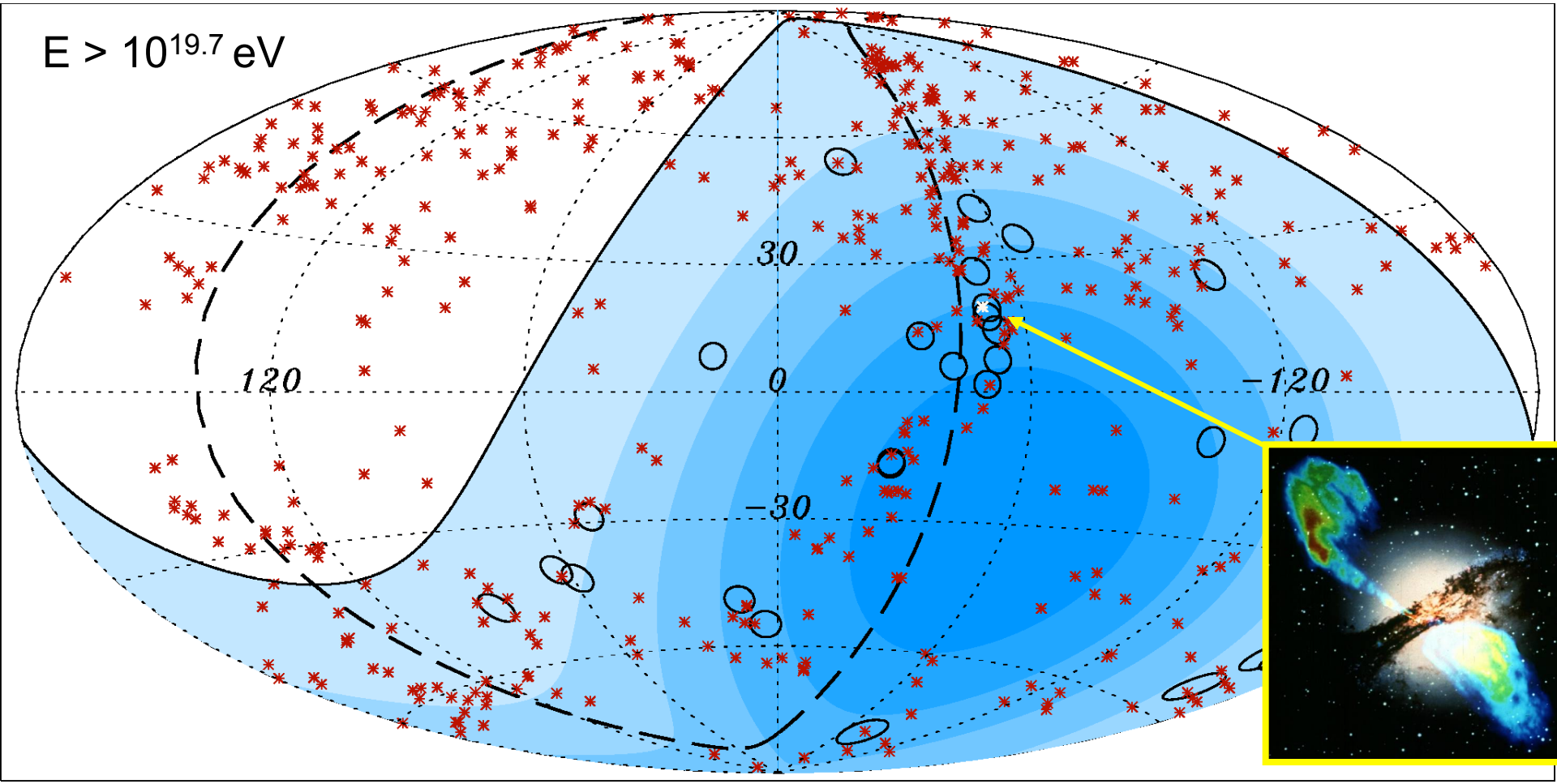
$E > 10^{19.6}$ eV

Cosmic rays and AGN's

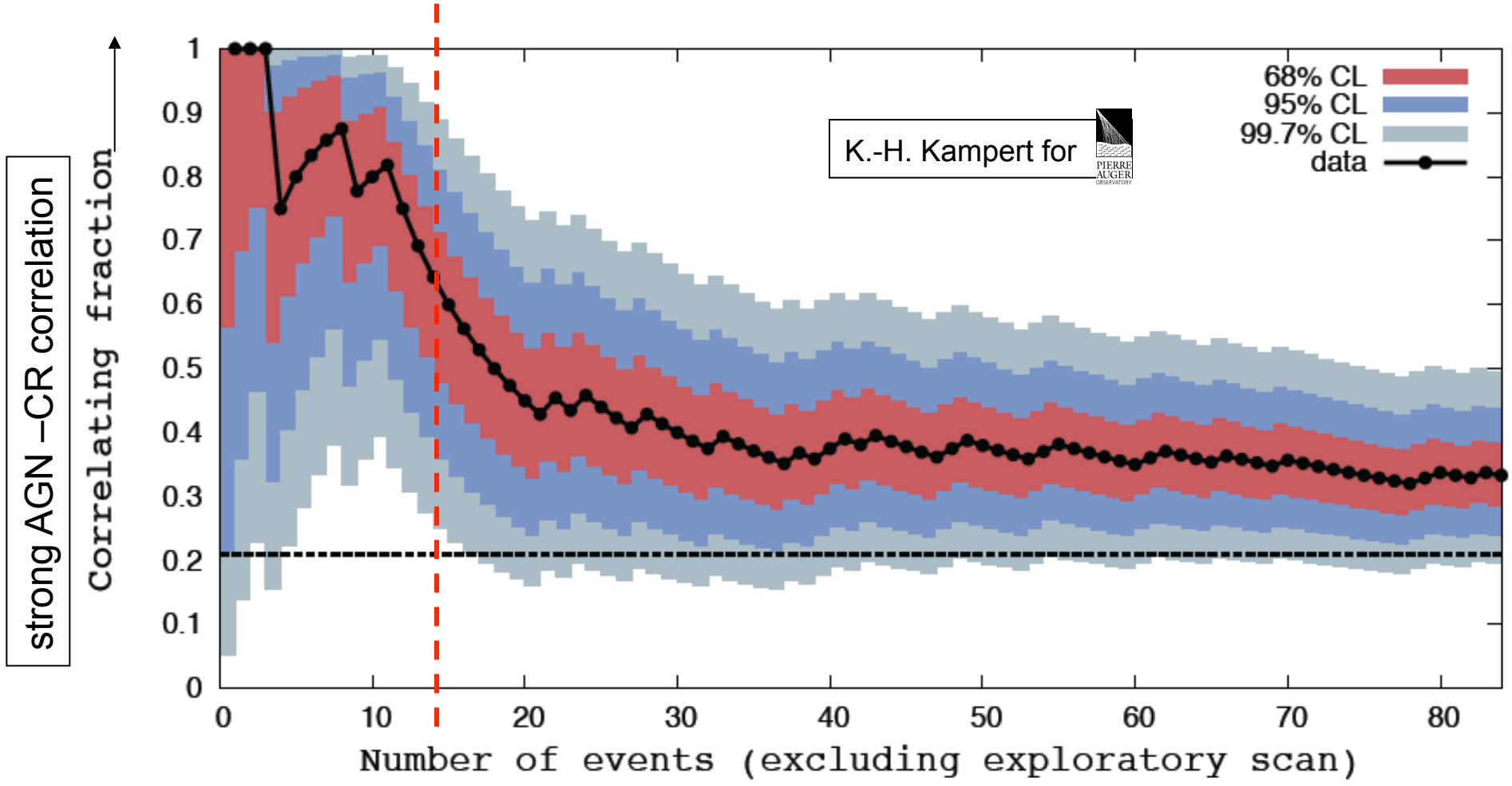




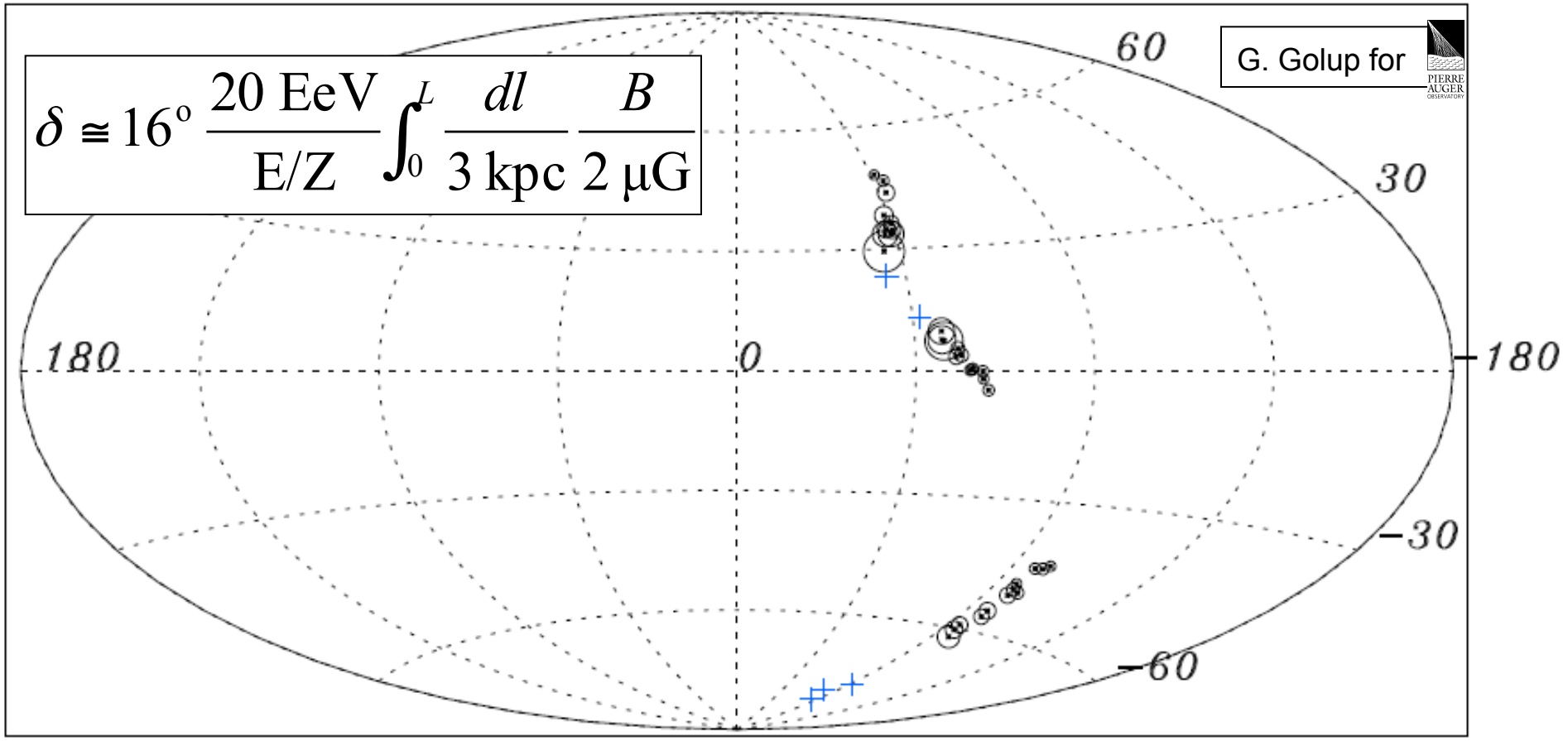
Cosmic rays and AGN's



Correlation signal is still significant



Multiplets (assuming protons)

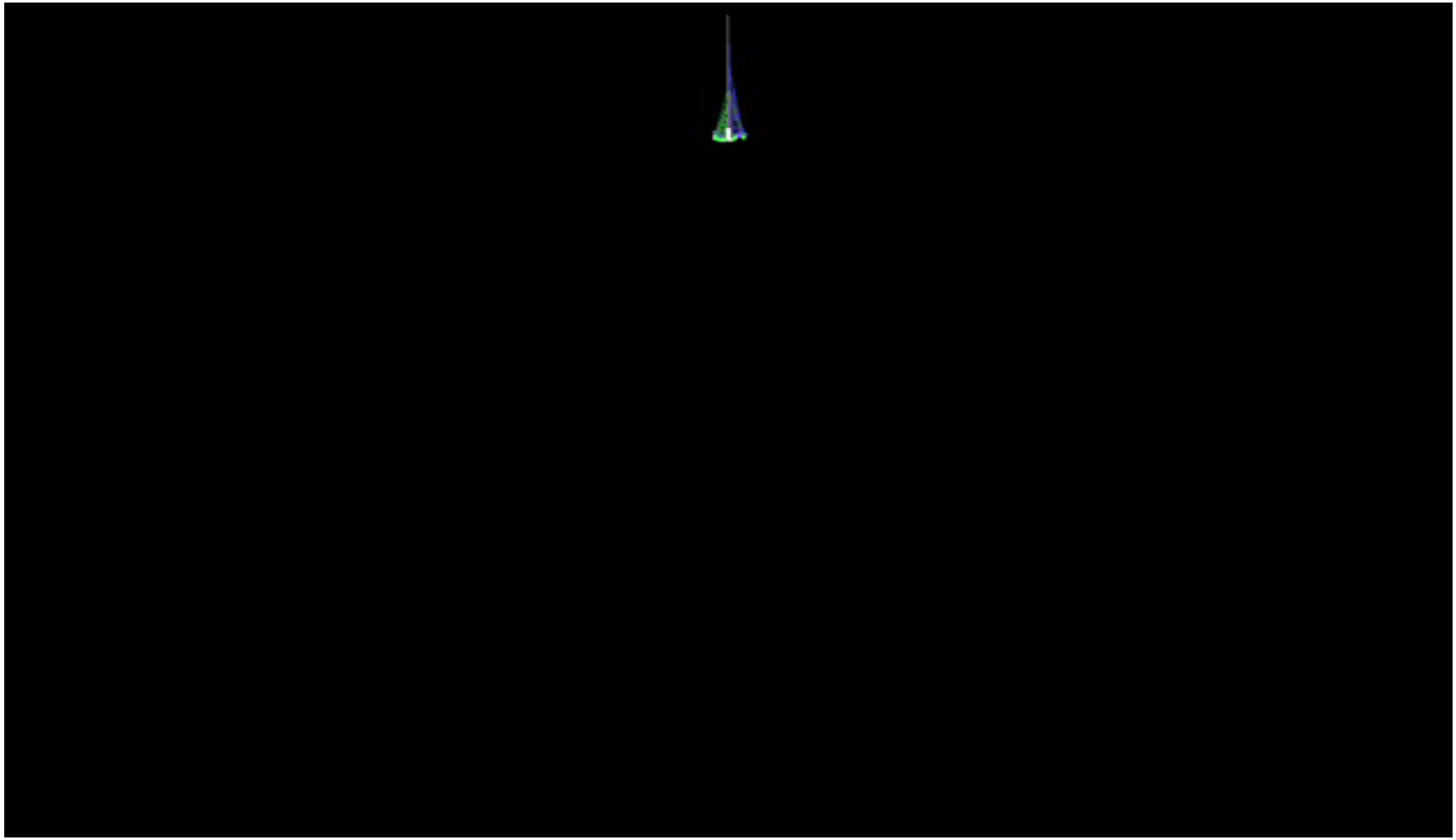


What does this mean?

- Strong correlation between identified source locations and arrival directions is hint for small deflection
  - light nuclei (low charge)?
  - low magnetic field? can we use CRs to determine B??
- Cutoff at the highest energies can be explained by
  - sources run out of steam; maximum Hillas value reached?
  - particles are protons which loose energy on their way to Earth through interactions with 2.7 K CMB photons?

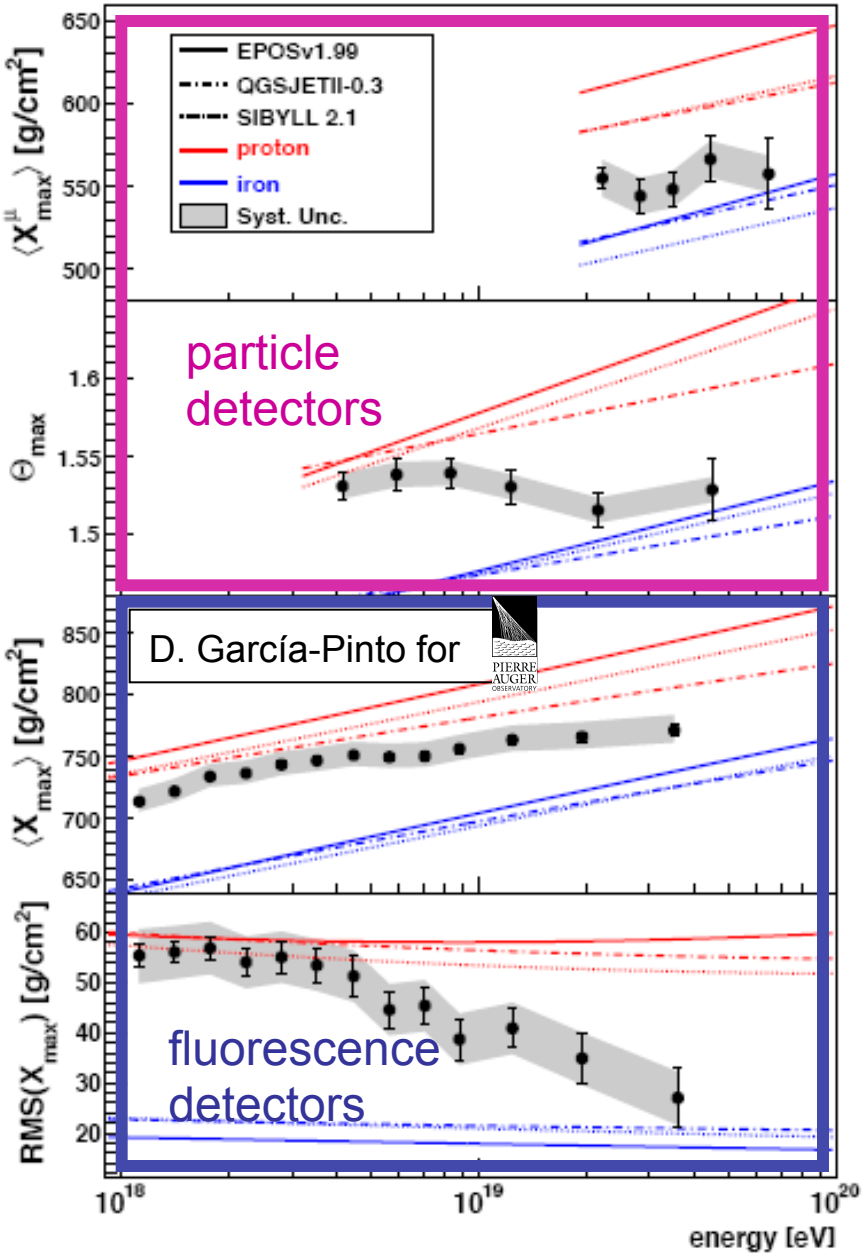
- Actually we don't know (yet); all experiments agree on the cutoff, but limited results on the charge/mass at high energies ($E > 10^{19.6}$ eV)

Airshower

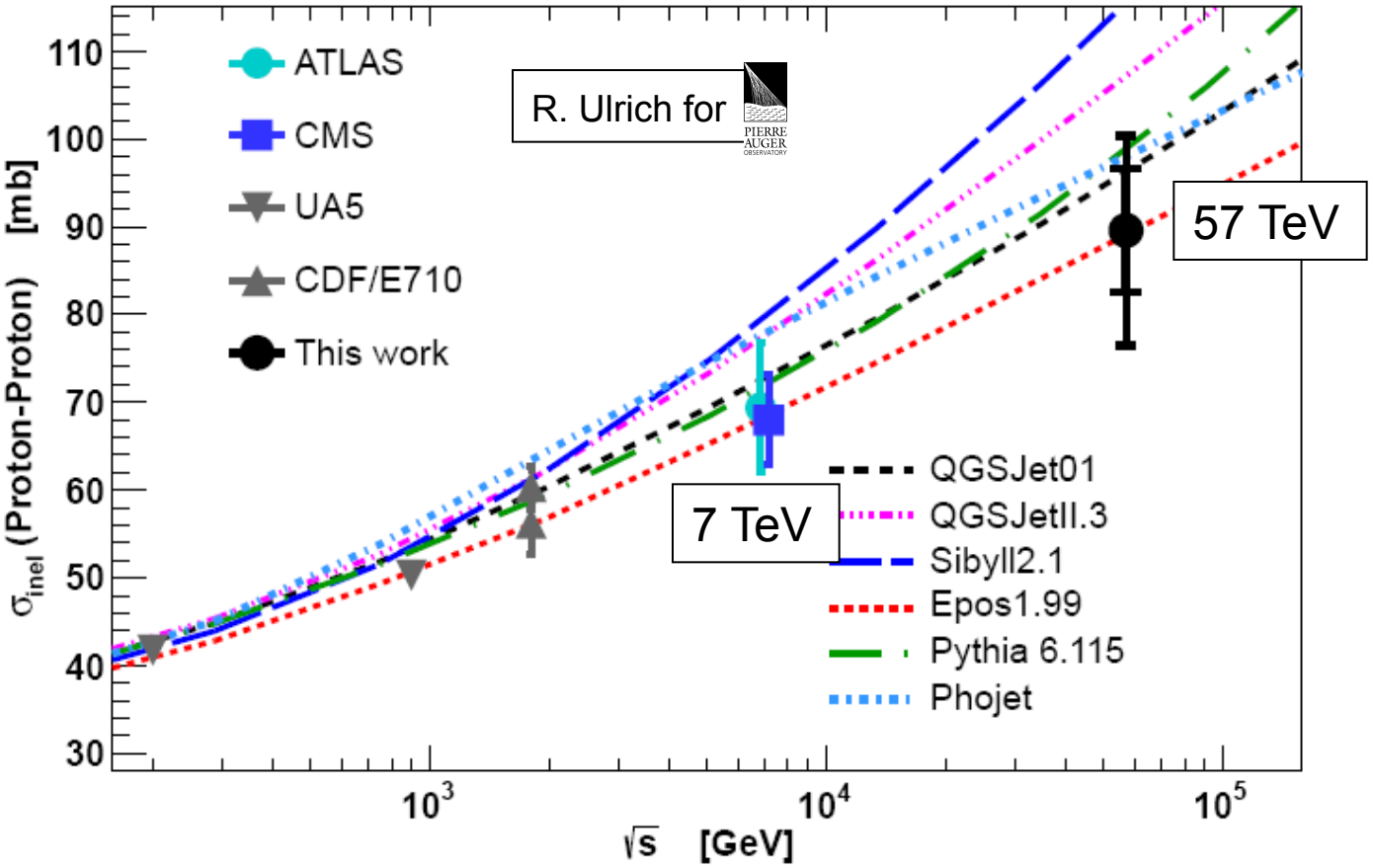


Composition

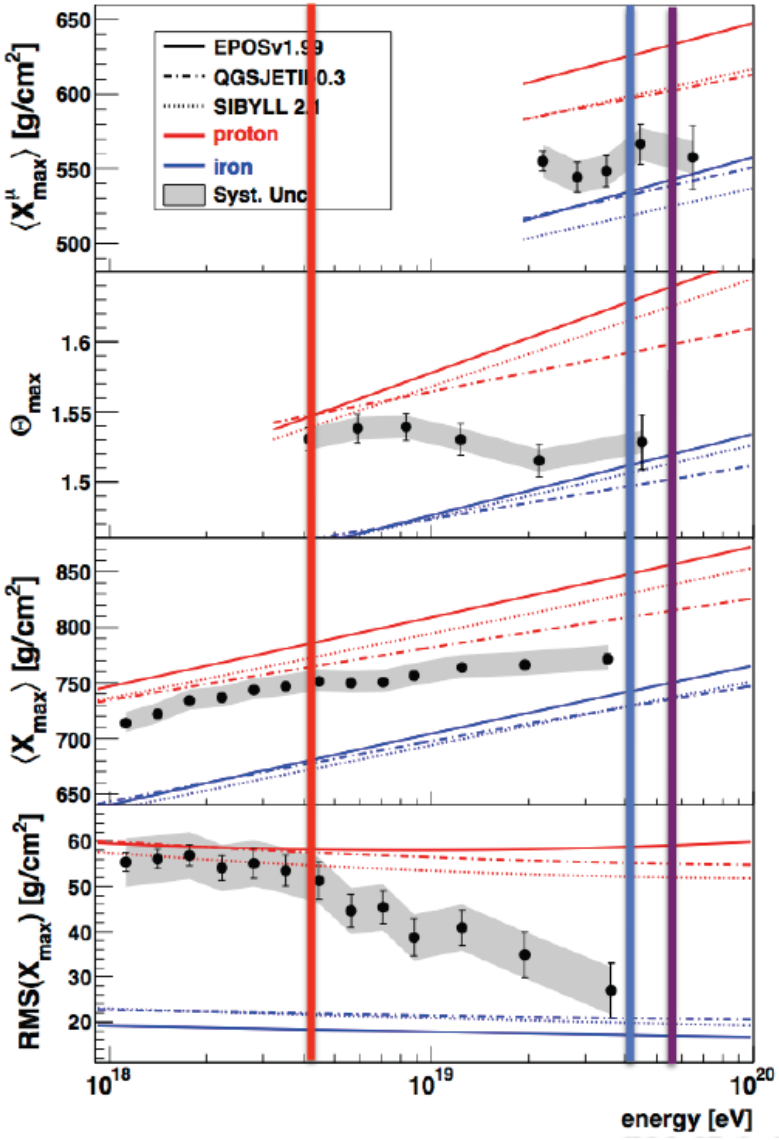
- The development of the particle shower in the atmosphere provides crucial information on composition
- **Arrival times of muons and electrons at the particle detectors**
- **1st and 2nd moment of the penetration depth profiles as function of E**



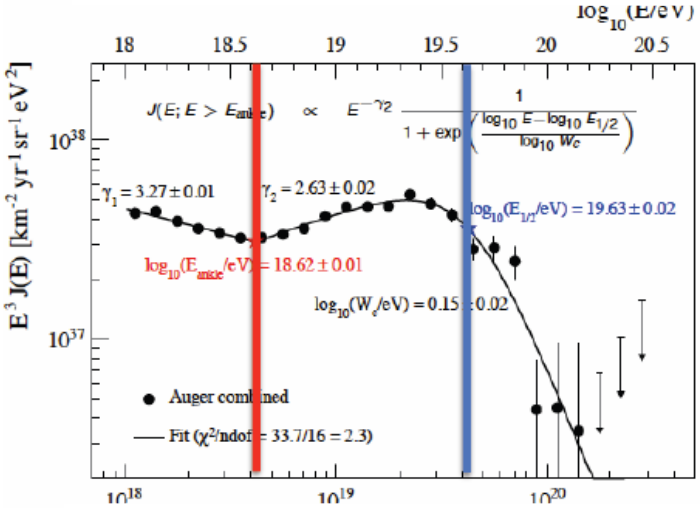
pp cross section @ TeV energy



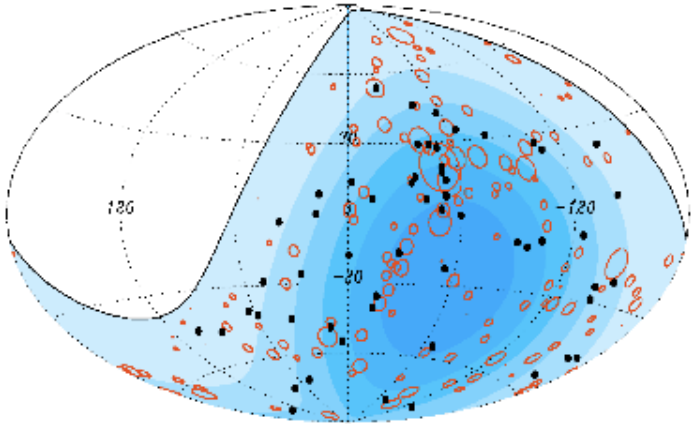
Composition



Spectrum



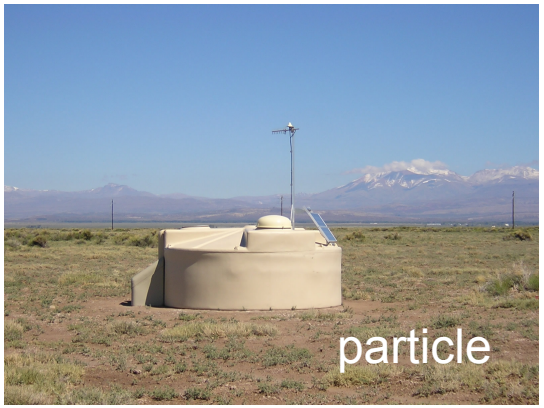
Sky distribution



Era of Super-hybrid

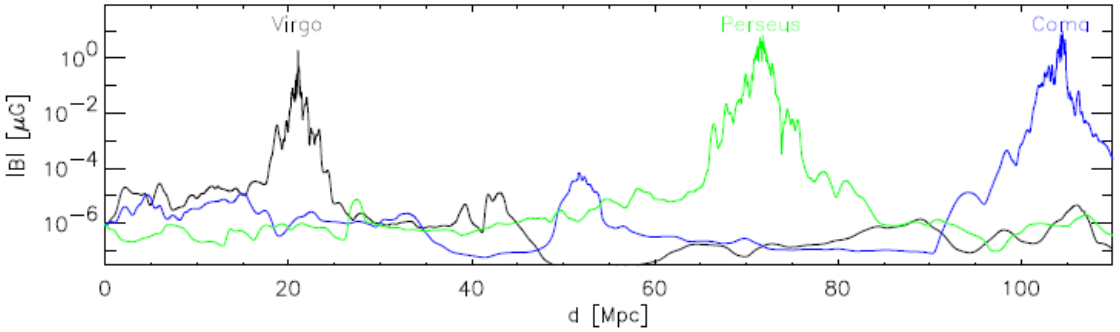
Victor F. Hess Nobel Lecture 1936:

To make further progress, particularly in the field of cosmic rays it will be necessary to apply all our resources and apparatus simultaneously and side-by-side

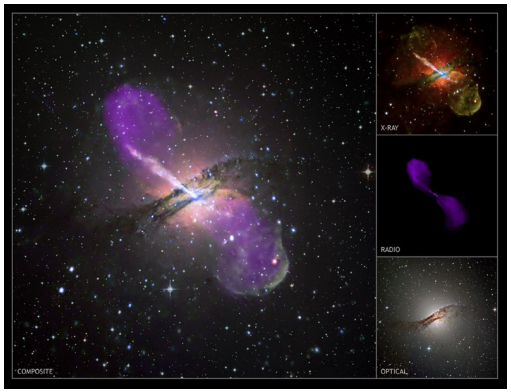


Road to understanding

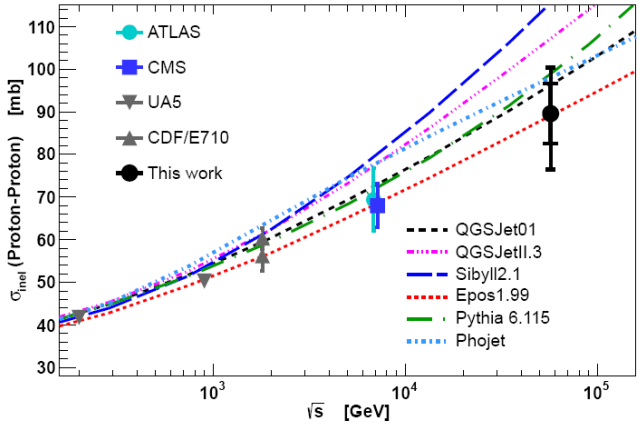
- intergalactic processes



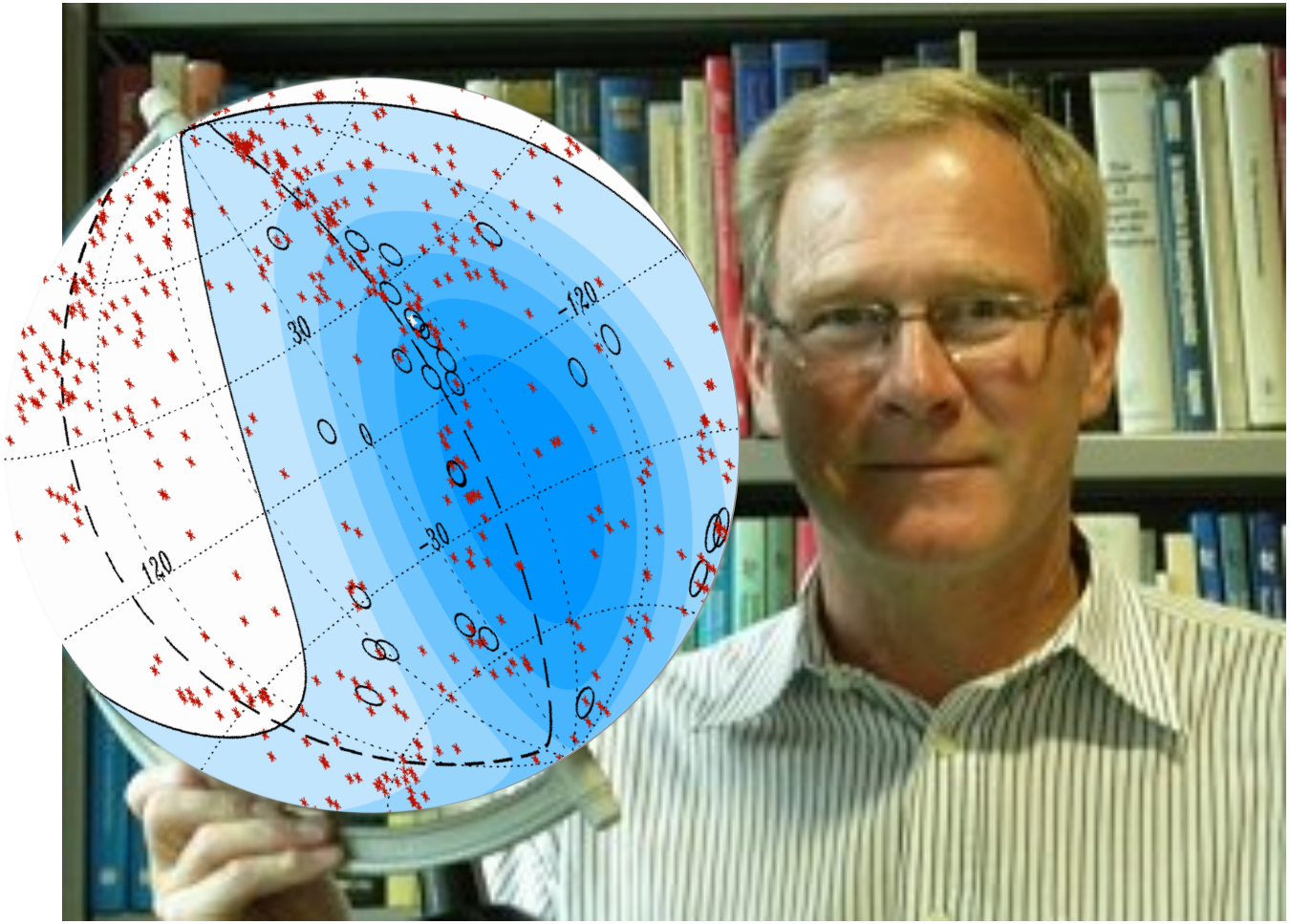
- sources



- interactions in the atmosphere



Jan Bedankt!



rijksuniversiteit groningen

Kernfysisch Versneller Instituut

Thanks for your attention

Pierre Auger Observatory

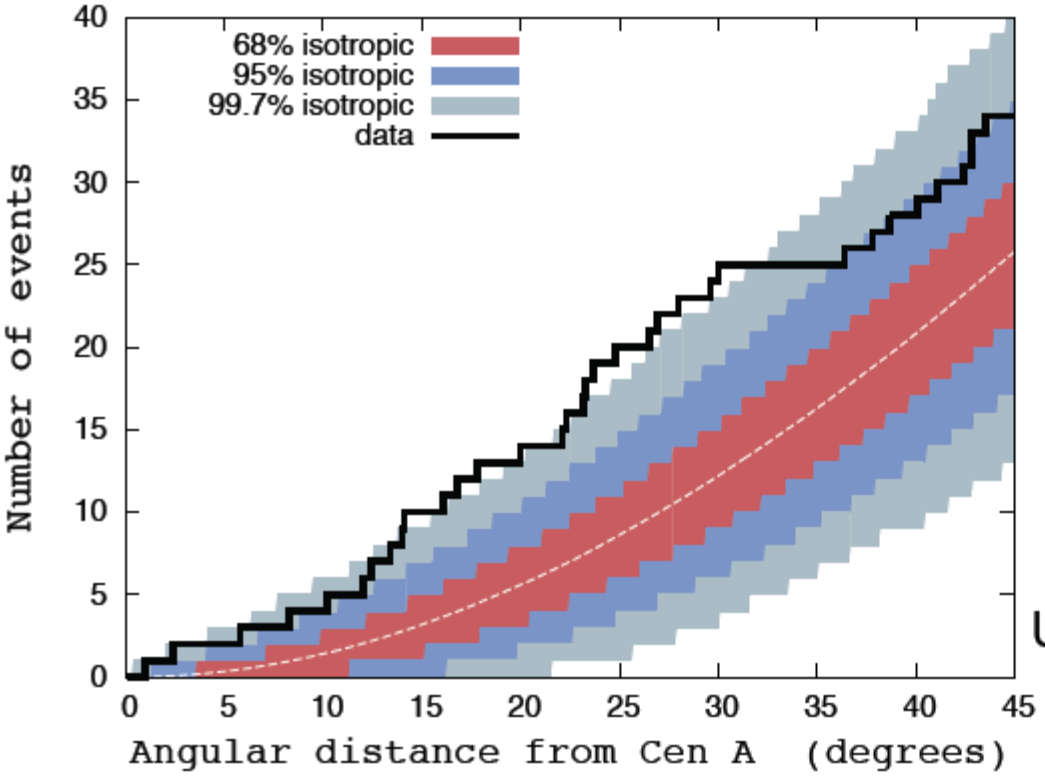
studying the universe's highest energy particles

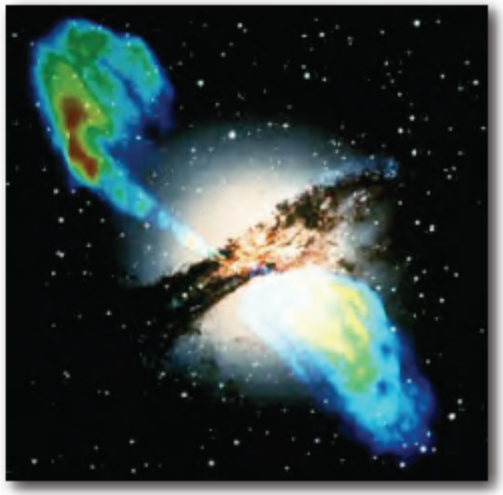
PIERRE AUGER OBSERVATORY

A. Aminaei[1], J. Coppens[1,2], K.D. de Vries[3], W. Docters[3], H. Falcke[1,4], E.D. Fraenkel[3], S. Grebe[1], S.J. de Jong[1], S. Harmsma[2,3], J.R. Hörandel[1], S. Jiraskova[1], J.L. Kelley[1], A. Nelles[1], J. Petrovic[2], H. Schoorlemmer[1], O. Scholten[3], C. Timmermans[2]

[1] Radboud University Nijmegen
[2] Nikhef
[3] University of Groningen
[4] Astron

Cen A





Update including June 2011