Raggi cosmici

- Particelle cariche stabili che incidono sull'alta atmosfera
  (vite media > 10^6 anni)
- Raggi cosmici *primari* (accelerati in sorgenti astofisiche)
- Raggi cosmici *secondari* (interazioni di raggi c. primari con gas interstellare)
- Elettroni, protoni, He, C, O, Fe… sintetizzati in stelle → ***primari***
- Li, Be, B (non abbondanti nella nucleosintesi stellare) →***secondari***
- Intensita': $\boldsymbol{dN/dE \sim 1.8 \times E^{-\alpha}}$ nucleoni/(m^2 s sr GeV/A)

  dove: E= energia per nucleone; α=2.7 (indice spettrale

  Energia: eV → MeV, GeV, TeV, PeV, EeV, ZeV

  10^6 10^9 10^{12} 10^{15} 10^{18} 10^{21} (eV)

Radiazione Cosmica

Include:

- **Particelle** (2% elettroni, 98% protoni e nuclei)
- **Fotoni**
- Energie elevatissime ($10^9 < E < 10^{20}$ eV)
- Fotoni di alta energia prodotti in collisioni di particelle cariche
- **Neutrini**

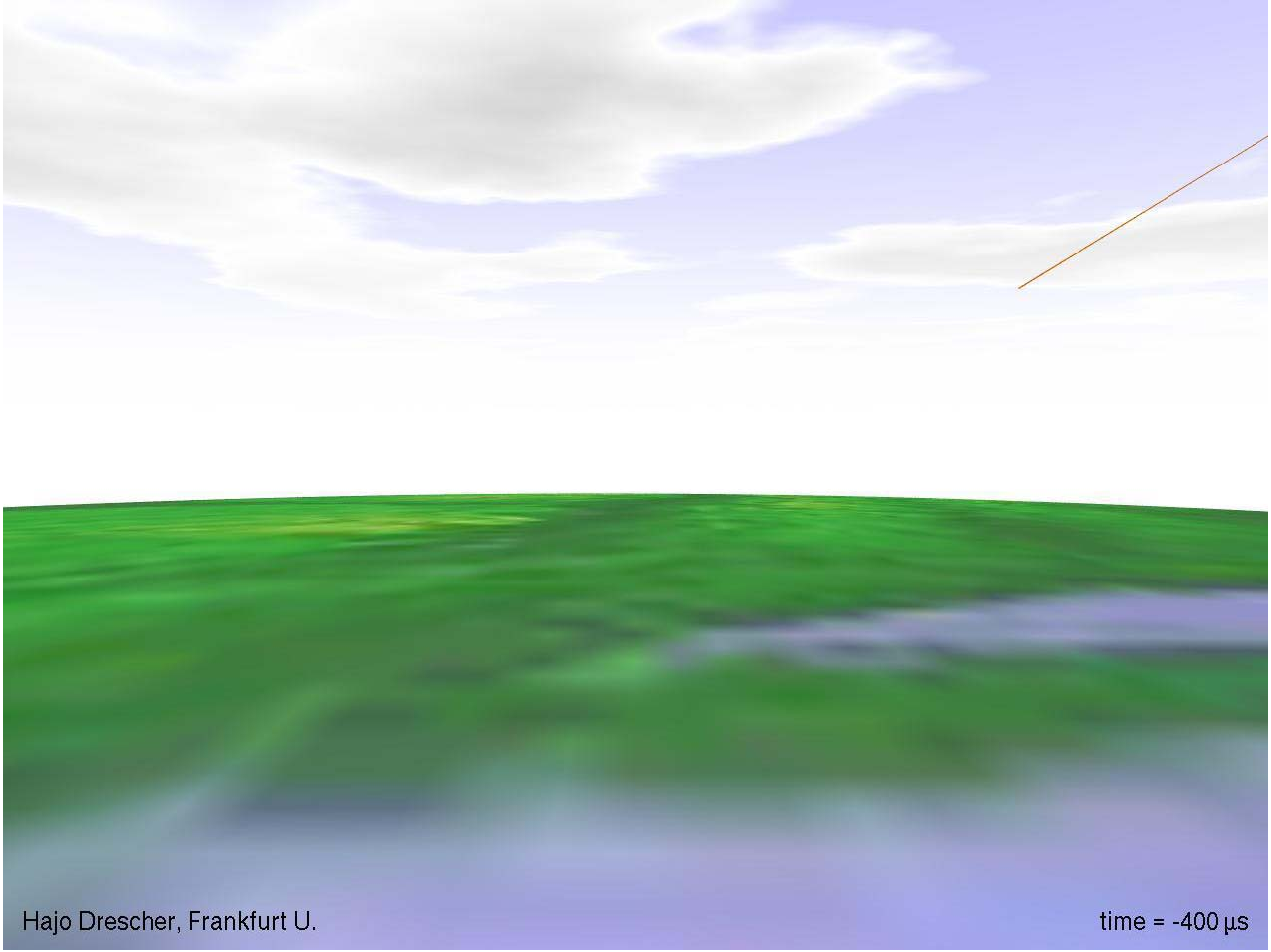
  Finora non visti (tranne quelli Solari e quelli dalla SN

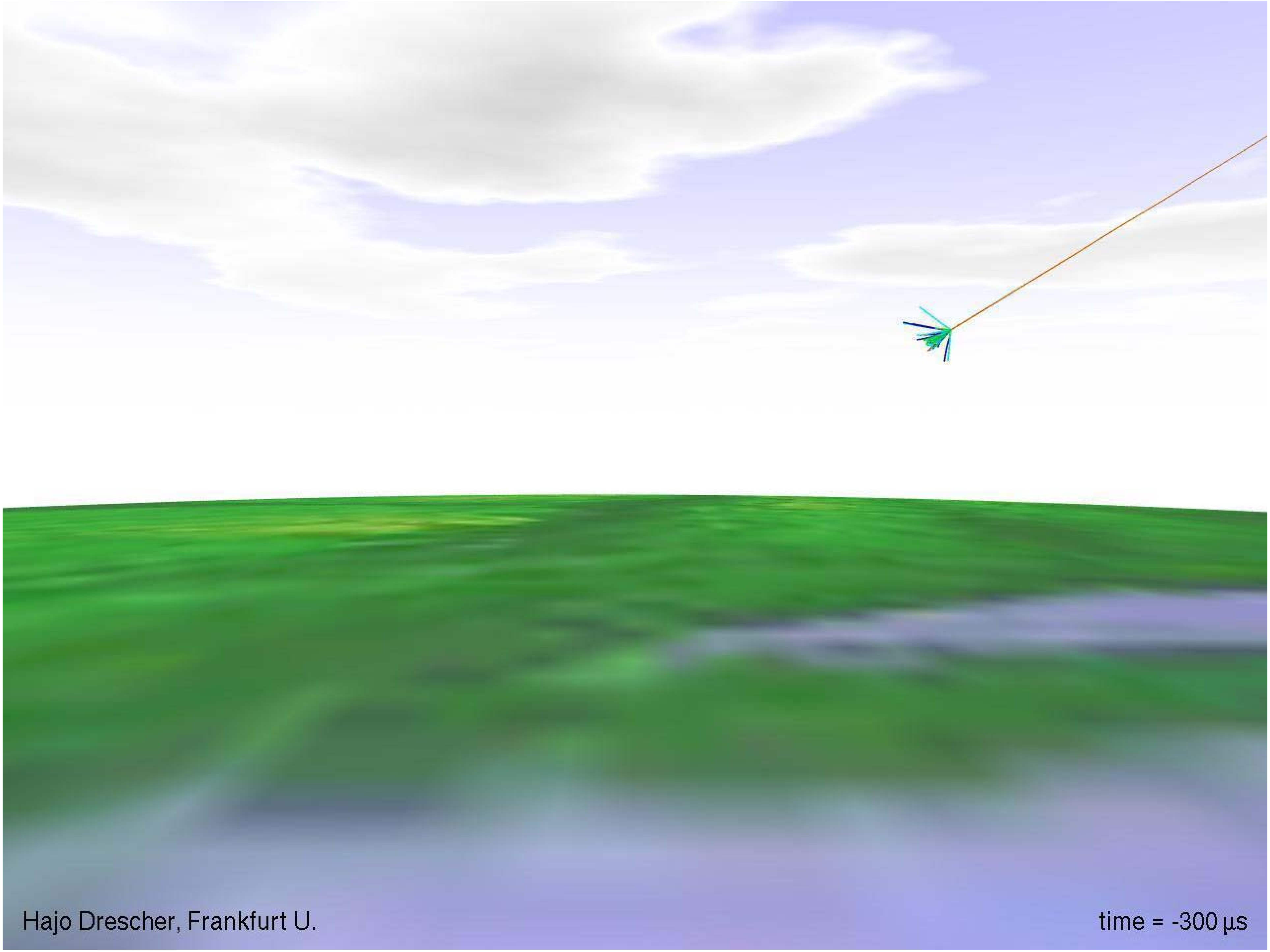
Implicazioni astrofisiche dei raggi cosmici

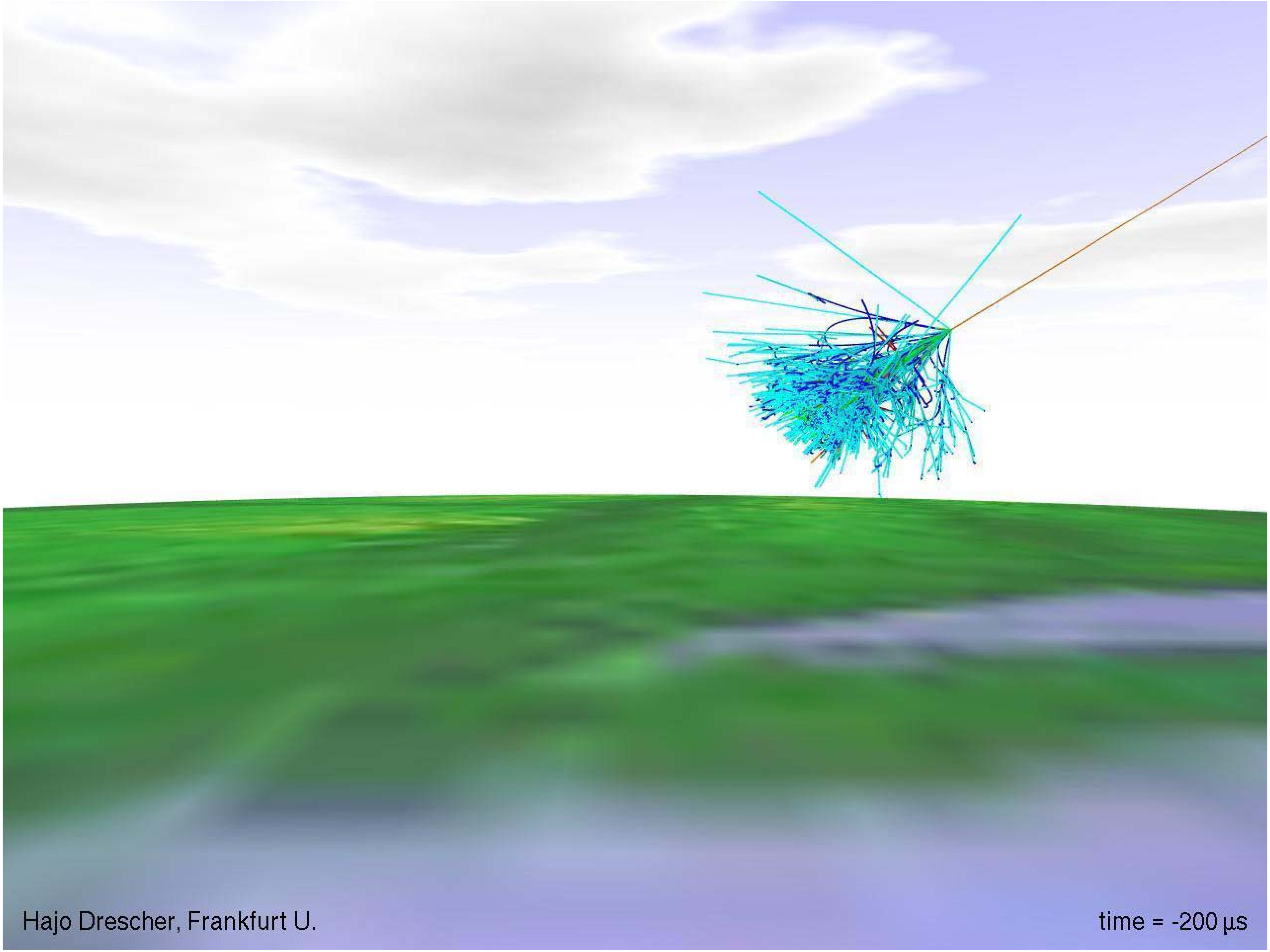
- Quale e' la loro origine ?
- Quale meccanismo li produce?
- Quali informazioni possono fornire sul mezzo che hanno attraversato ?
- Raggi cosmici **‘Primari’** possono esser rivelati solo al di sopra dell’atmosfera terrestre.

Raggi cosmici primari e secondari

- I campi magnetici della Terra e del Sole deflettono i **primari** raggi cosmici primari (sopratutto quelli di bassa energia).
- Solo le particelle **secondarie** raggiungono il suolo - ed esse possono coprire aree molto ampie ~ molti km^2
- "Sciami estesi" che possono depositare fino a 10^{10} particelle/km^2 - positivo per la rivelazione


Hajo Drescher, Frankfurt U.
time = -400 µs


Hajo Drescher, Frankfurt U.
time = -300 µs


Hajo Drescher, Frankfurt U.
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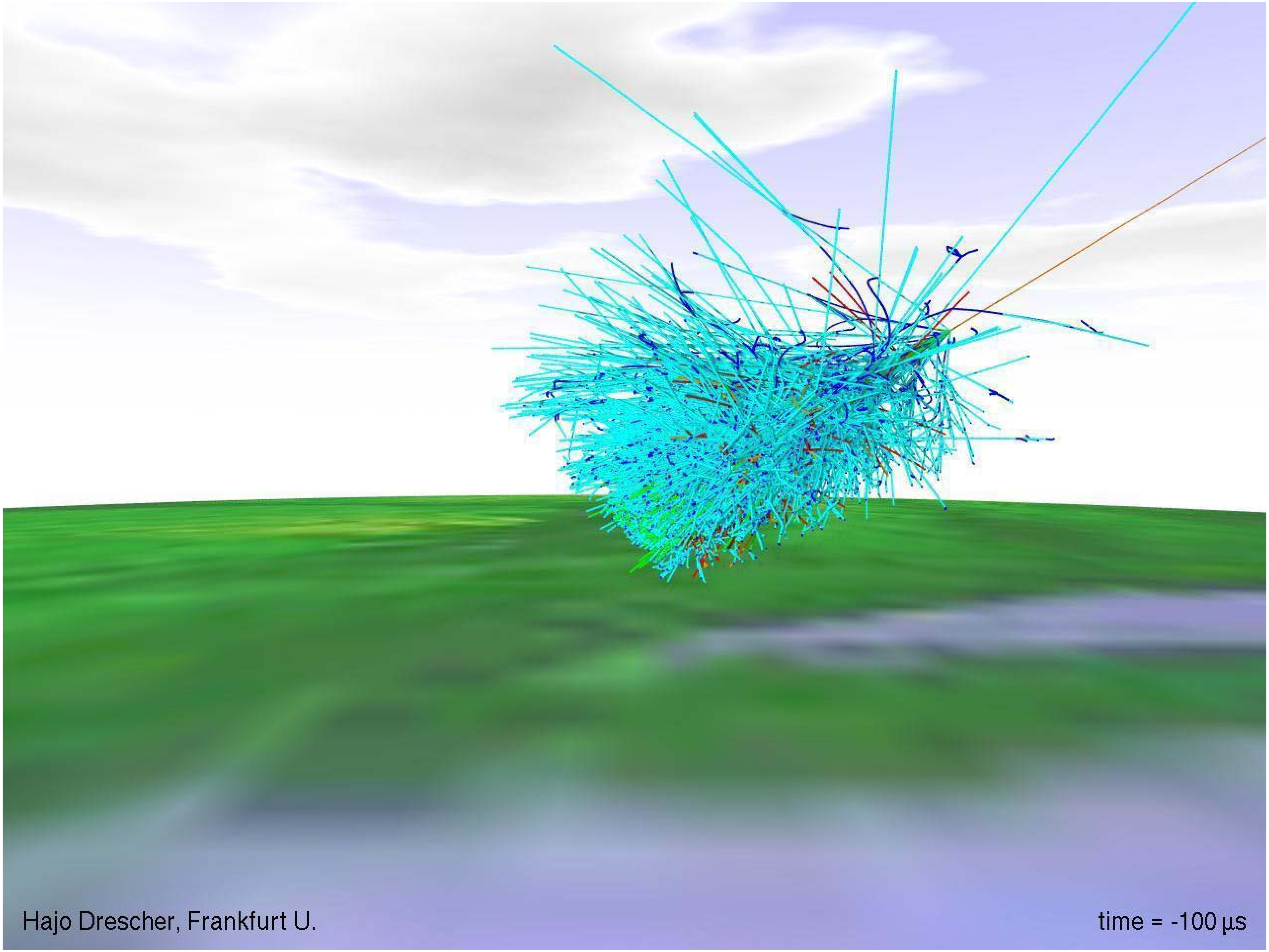
Hajo Drescher, Frankfurt U.
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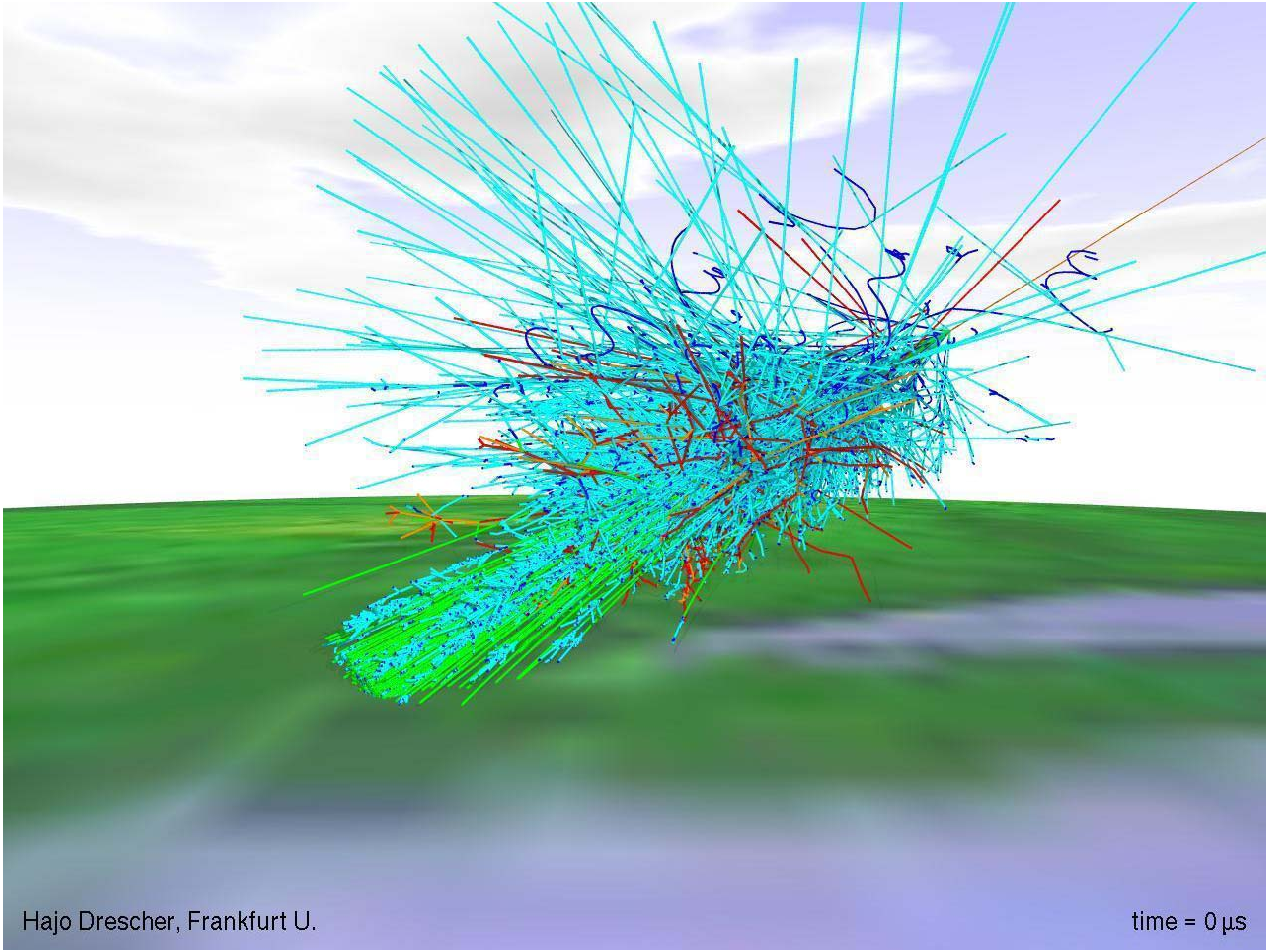
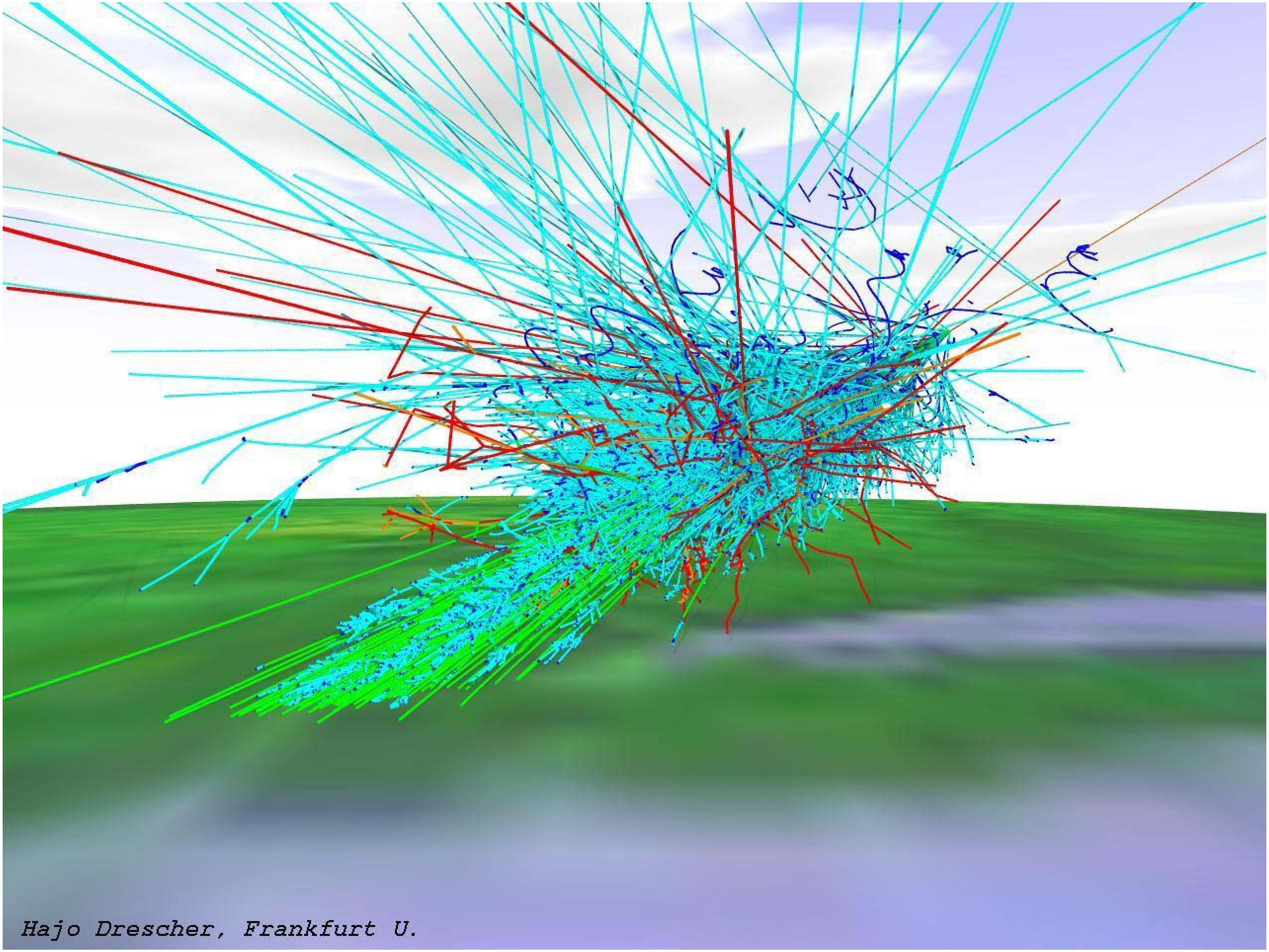
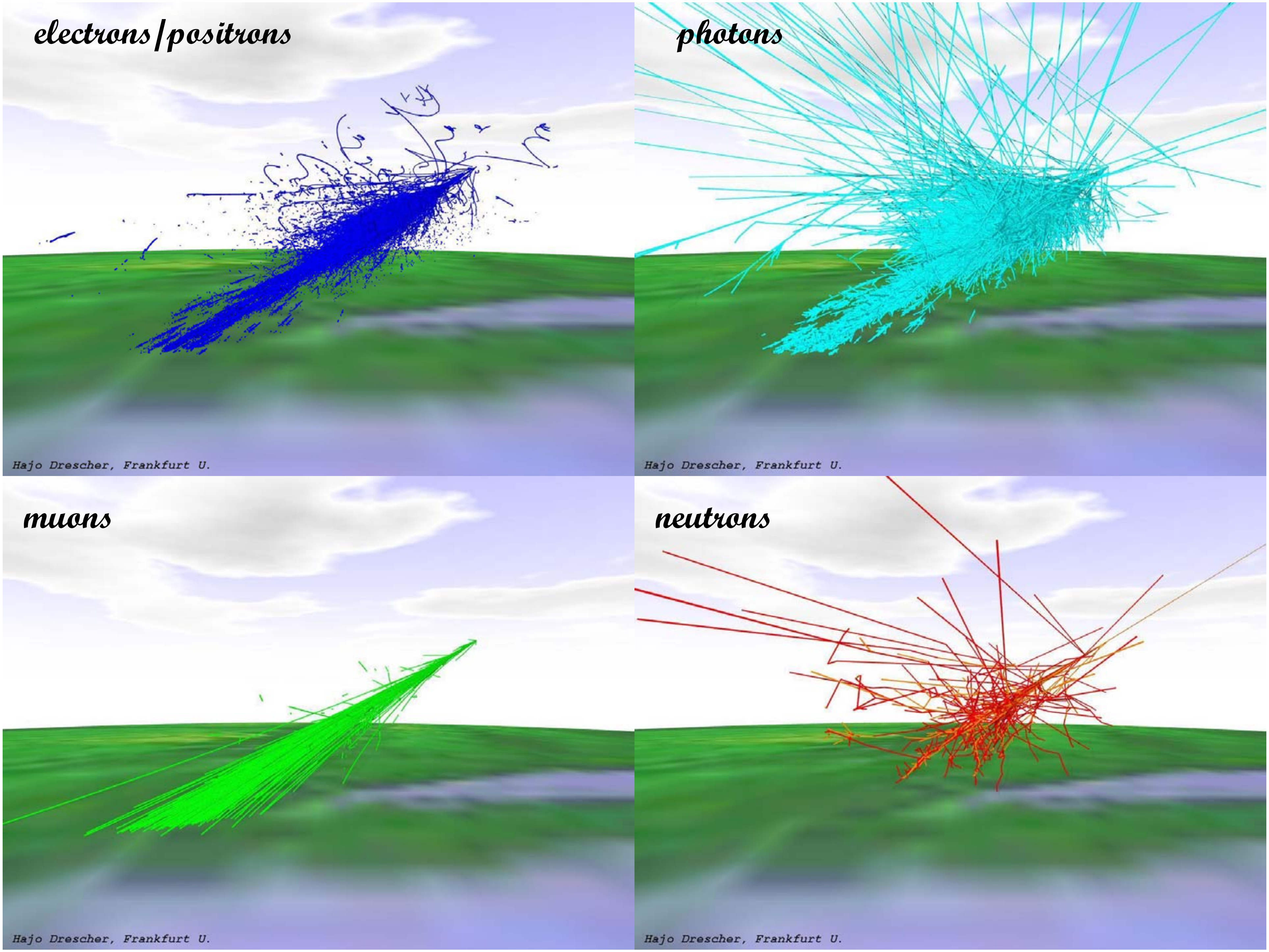

Hajo Drescher, Frankfurt U.
time = 0 µs


Hajo Drescher, Frankfurt U.


electrons/positrons
Hajo Drescher, Frankfurt U.
photons
Hajo Drescher, Frankfurt U.
muons
Hajo Drescher, Frankfurt U.
neutrons
Hajo Drescher, Frankfurt U.

Rivelatori

- Contatori Geiger
- Contatori a scintillazione
- Rivelatori Cerenkov
- Contatori a piastre resistive

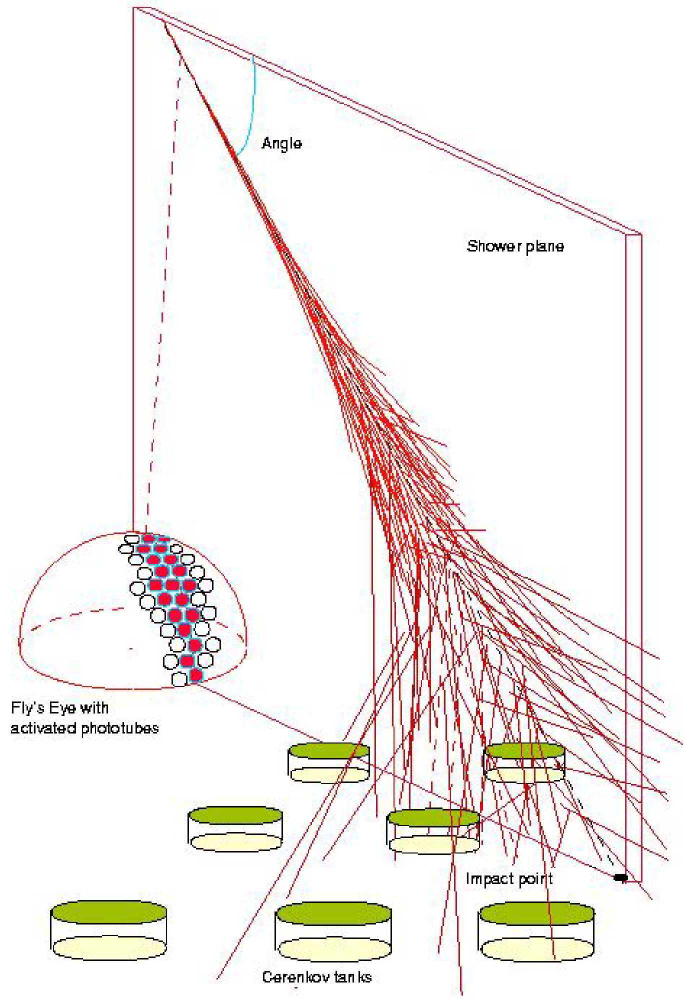
- Enormi “matrici” di rivelatori disposte a terra, coprendo grandi estensioni

Shower Arrays

Detection Techniques

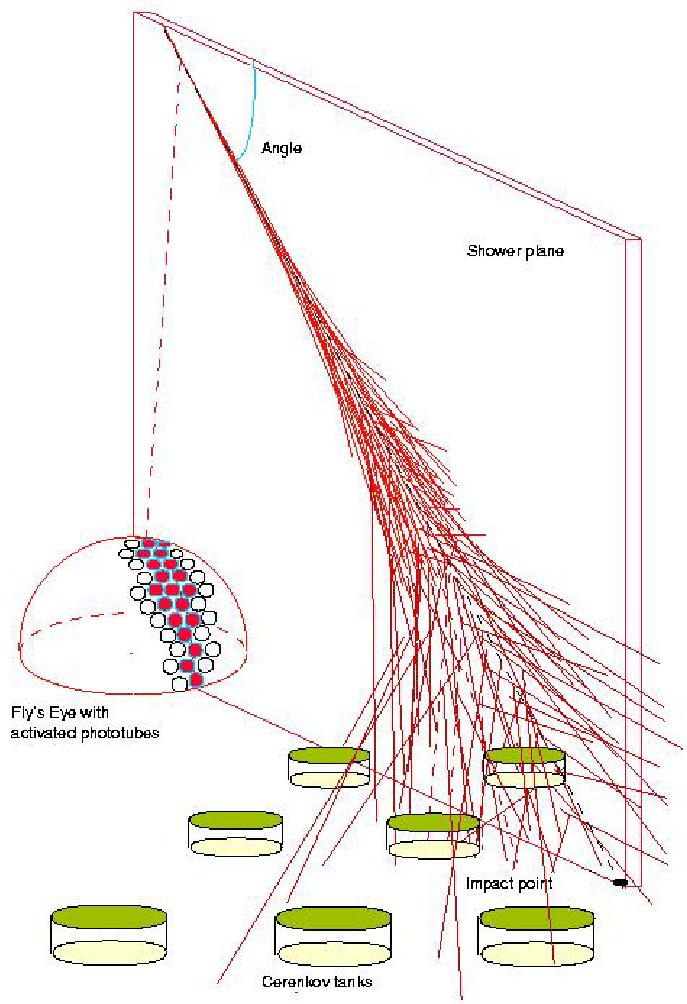
- **Ground arrays sample the shower front arriving at ground level**
- **~ 100% duty cycle**
- **Shower is sampled at one altitude only, development of the shower in the atmosphere is not seen**

- **AGASA (Akeno Giant Air Shower Array)**
  - **Operated in Japan 1984-2003**
  - **– 111 scintillation counters of 2.2 m^2 area each**
  - **– 100 km^2 area, about 1 km spacing**



Detection Techniques

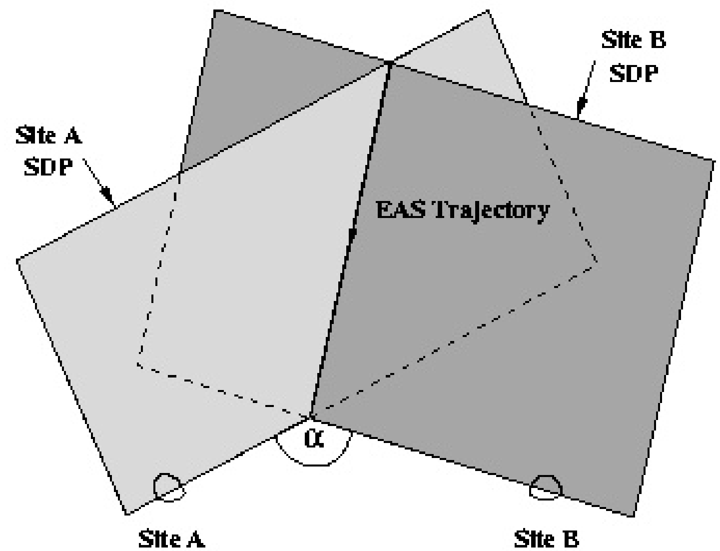
- **Particles of the air shower cascade excite air molecules, which fluoresce in the UV**
- **Fluorescence light can be detected with photomultipliers observing the night sky - the shower is seen by a succession of tubes**
- **Air fluorescence detectors observe shower development in the atmosphere and provide a nearly calorimetric energy estimate**
- **Large instantaneous detector volume**
- **Operation on clear, moonless nights with good atmospheric conditions, so small duty cycle of 8 to 10%**



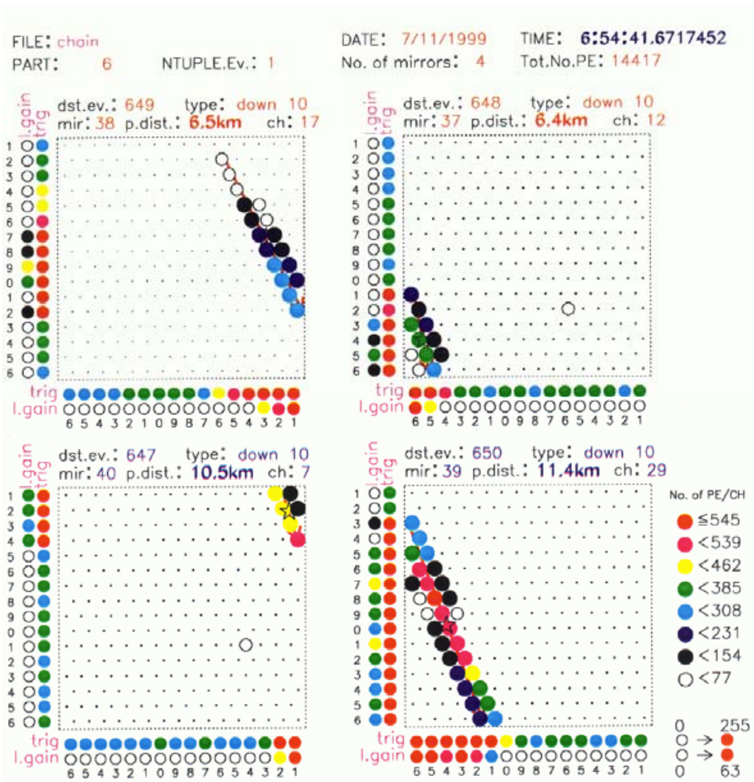
Detection Techniques

- **Monocular track gives shower-detector plane to high accuracy, but position of shower within the plane is (rather poorly) determined using the PMT times**
- **Stereo viewing of the showers with two air fluorescence detectors breaks the ambiguity and leads to excellent angular resolution ~0.5°**

- **HiRes (High Resolution Fly's Eye)**
  – **Operated in Utah since 1996, as a stereo detector since 1999**
    - **2 sites (HiRes 1&2), 12.6 km apart**



HiRes PMT Camera

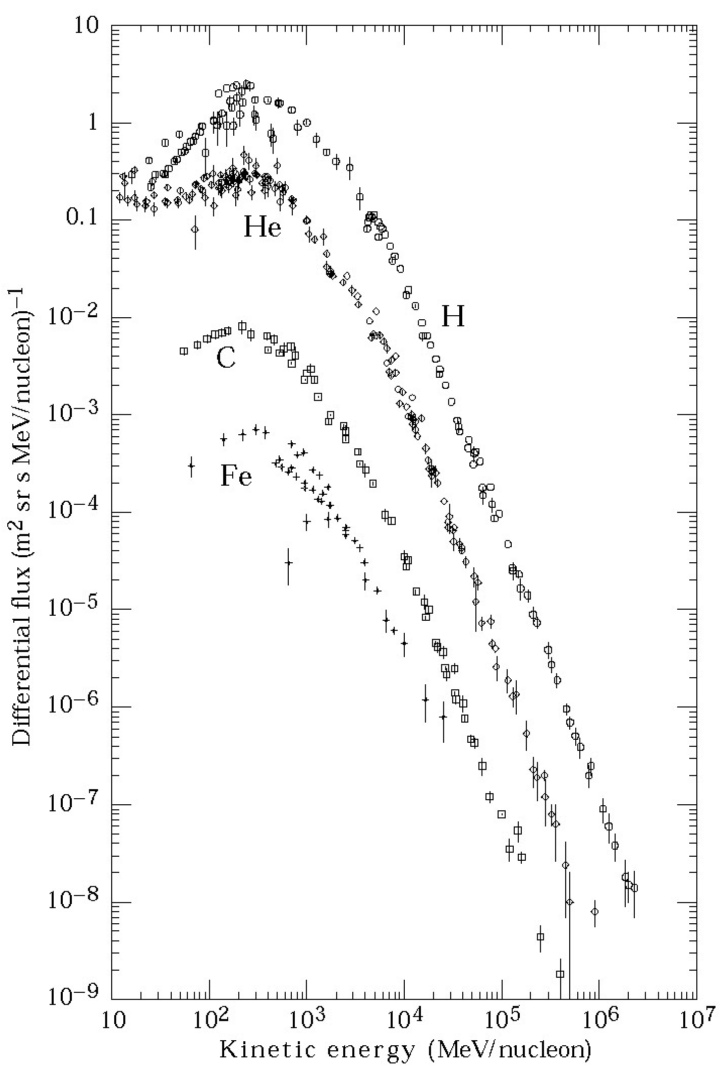


Caratteristiche dei RC

- Parametri d'interesse:

  - Composizione chimica
  - Spettri d'energia
  - Isotropia
  - Origine

Flussi differenziali



Z	Elemento	Flusso relativo
1	H	540
2	He	26
3-5	Li-B	0.40
6-8	C-O	2.20
9-10	F-Ne	0.30

Flusso di elettroni circa due ordini di grandezza inferiore a quello dei protoni

Flusso di positroni circa 1/20 di quello degli elettroni

Flusso di antiprotoni circa un decimillesimo di quello dei protoni

Effetti del campo magnetico

Osservazioni della dipendenza dalla latitudine

Particelle di basso impulso vengono curvate dal campo magnetico terrestre e non raggiungono la sommita' dell'atmosfera (e men che mai la terra!). L'effetto e' piu' rilevante alle piccole latitudini, dove e' maggiore l'integrale del campo lungo la traiettoria

Deflessione in campo magnetico

Raggio di curvatura: r=E/(300 B Z)

dove: r in cm; E in eV; B in gauss; Z in unita' di carica dell'elettrone

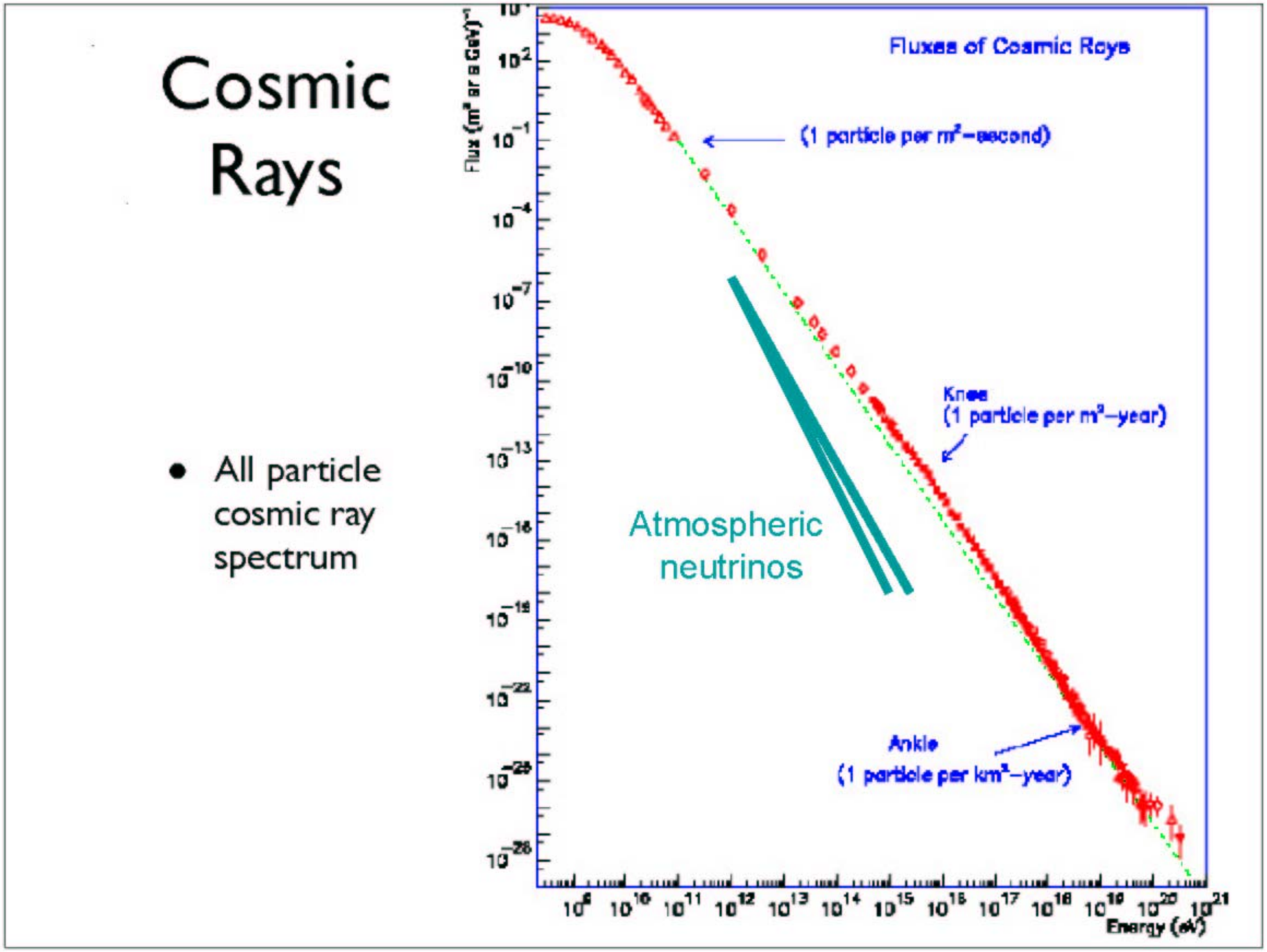
o anche: r=E/(0.3 B Z)

dove: r in m; E in GeV; B in Tesla; Z in unita' di carica dell'elettrone

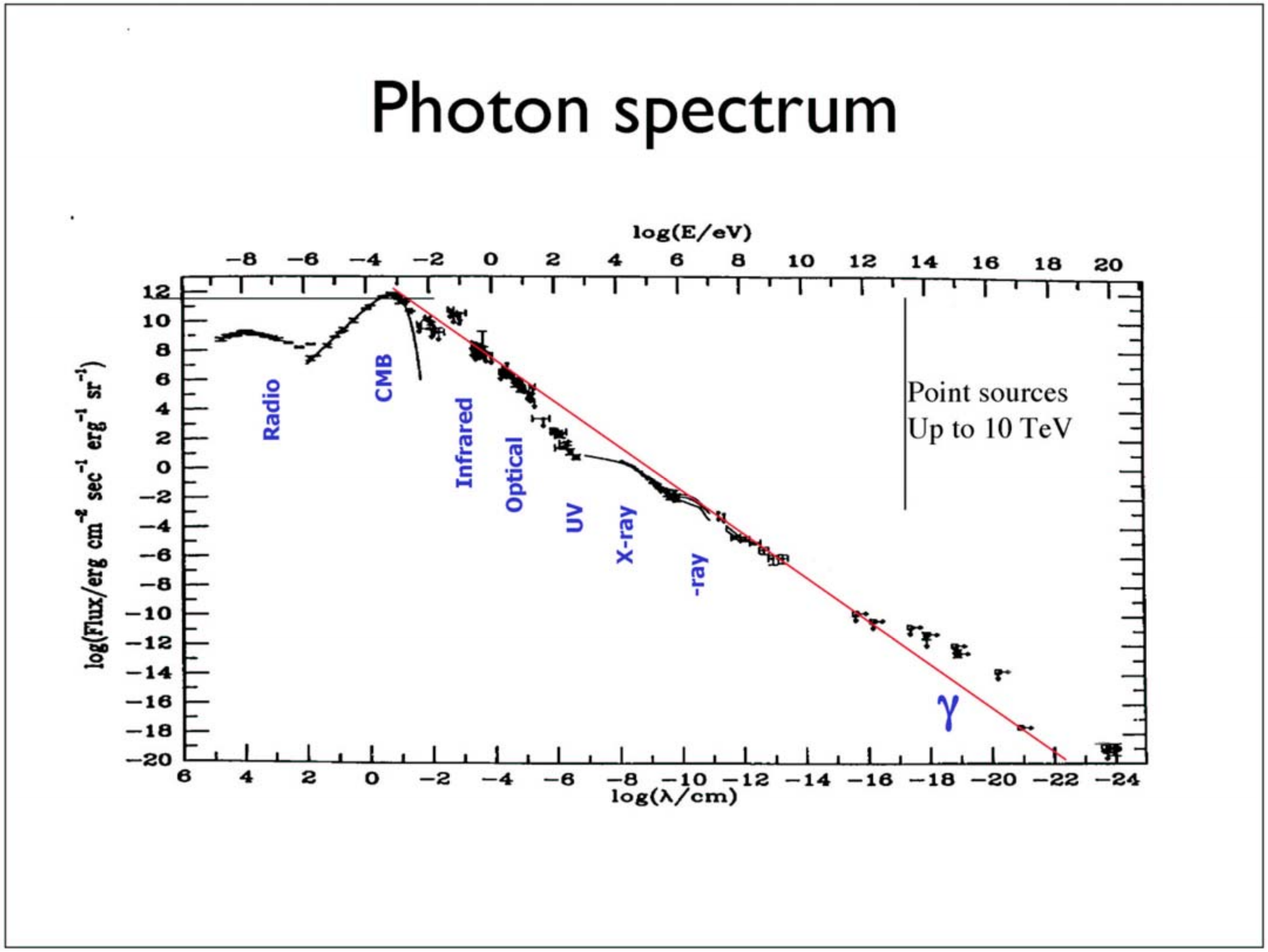
Da cui: E=0.3 B r Z

Spettro dei raggi cosmici

Flusso ~ $E^{-\alpha}$ con α =2.7



Fotoni



Photon spectrum
log(E/eV)
−8 −6 −4 −2 0 2 4 6 8 10 12 14 16 18 20
12 10 8 6 4 2 0 −2 −4 −6 −8 −10 −12 −14 −16 −18 −20
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
Radio
CMB
Infrared
Optical
UV
X-ray
-ray
Point sources
Up to 10 TeV
γ
6 4 2 0 −2 −4 −6 −8 −10 −12 −14 −16 −18 −20 −22 −24
log(λ/cm)

Greisen-Zatsepin-Kuzmin cutoff

$P + \gamma \to n + \pi^+$

$(E+\varepsilon)^2-(P-\varepsilon)^2 = E^2 - P^2 + 4\,\varepsilon\,E = (940+140)^2\ \mathrm{MeV}^2 =$

$=(1.08\ \ 10^9)^2\ \mathrm{eV}^2 \Rightarrow E_{max} = 7\ 10^{19}\ \mathrm{eV}$

Calcolo dettagliato → *E_{max} ~ 50 EeV*

Lunghezza d'assorbimento ~ 10 Mpc (sopra i 50 EeV)

$[\lambda_{\gamma p} = (n_{CMB}\,\sigma_{p+\gamma_{CMB}})^{-1}]$

con n_{CMB}=400 cm^{-3} e $\sigma_{p+\gamma_{CMB}}$ =10^{-28} cm^2]

Il che implica che raggi cosmici di energia superiore a 50 EeV non possono aver origine da distanze superiori a circa 50 Mpc

Interazioni con il CMB

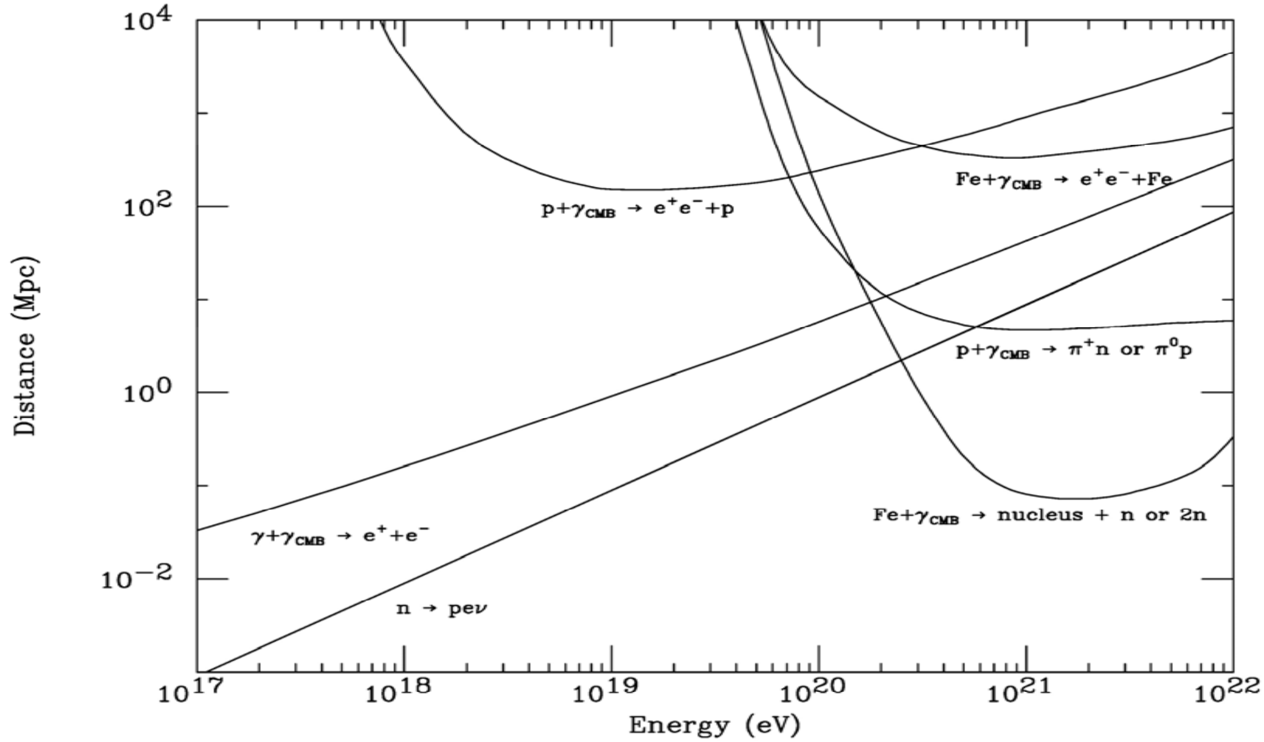
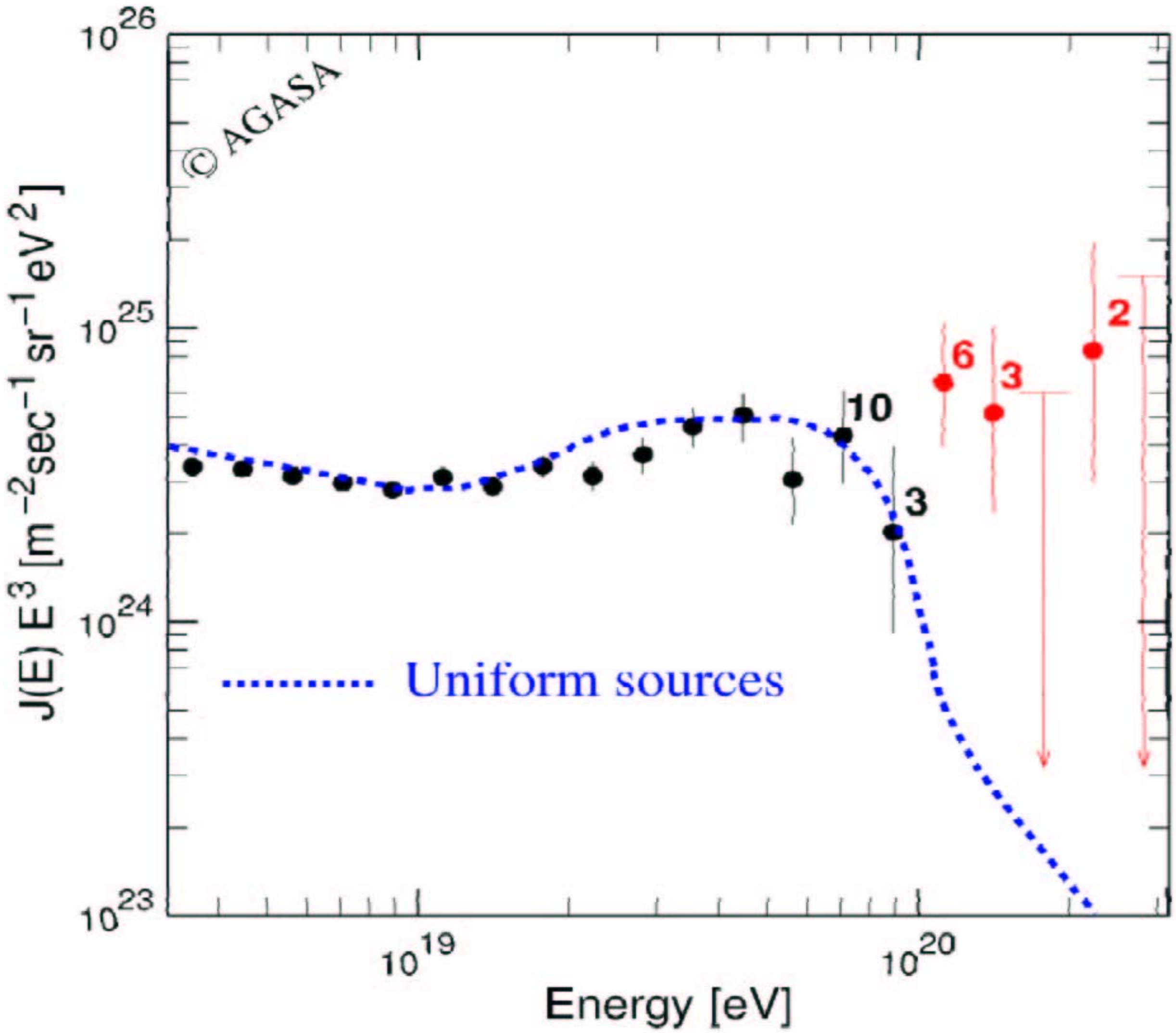


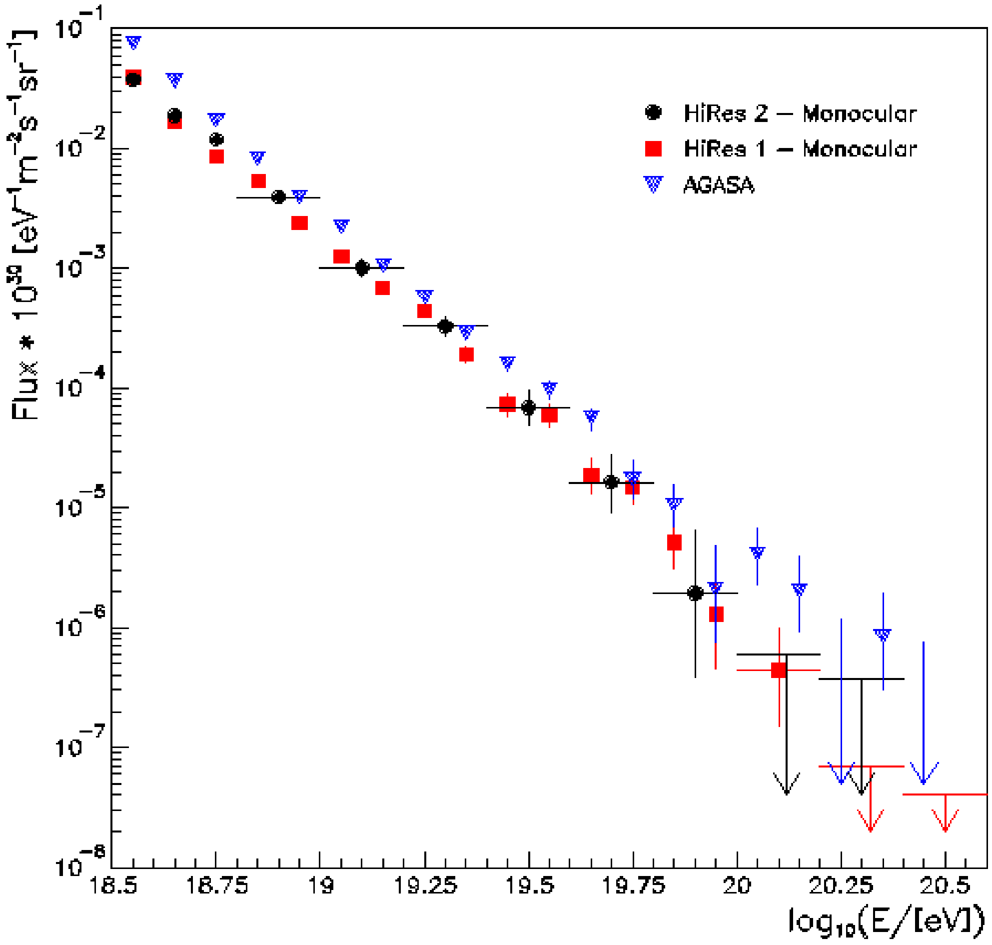
Figure 3: Panorama of the interactions of possible cosmic primaries with the CMB. Curves marked by "$p+\gamma_{CMB} \rightarrow e^+e^-+p$" and "$Fe+\gamma_{CMB} \rightarrow e^+e^-+p$" are energy loss lengths (the distance for which the proton or Fe nucleus loses 1/e of its energy due to pair production). The curve marked by "$p+\gamma_{CMB} \rightarrow \pi^+n$ or $\pi^\circ p$" is the mean free path for photo-pion production of a proton on the CMB. The curve marked "$Fe+\gamma_{CMB} \rightarrow$ nucleus + n or 2n" is the mean free path for a photo-nuclear reaction where one or two nucleons are chipped off the nucleus. The curve marked "$\gamma+\gamma_{CMB} \rightarrow e^+e^-$" is the mean free path for the interaction of a high-energy photon with the CMB. Added for reference is the mean decay length for a neutron indicated by "$n \rightarrow pe\nu$".

GZK cutoff ?



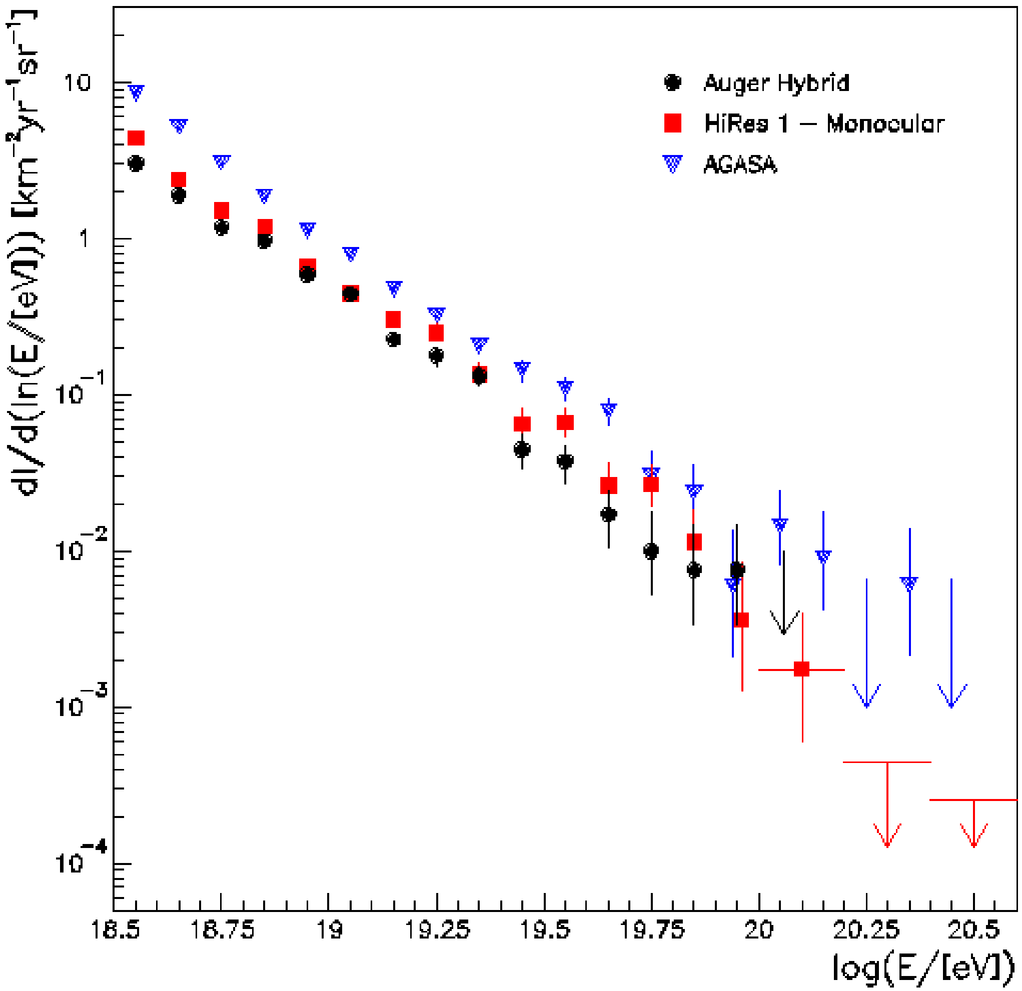
HiRes *vs* AGASA Flux

- **Below 10^{20} eV, the two spectra agree within systematic uncertainties**
- **Above 10^{20} eV, the discrepancy has low statistical significance** *D. De Marco, P. Blasi, A.V. Olinto, Astroparticle Phys. 20(2003) 53*
- **Need *much* larger statistics above 10^{20} eV to claim GZK violation**
- ***Both* experiments observe events above 10^{20} eV**



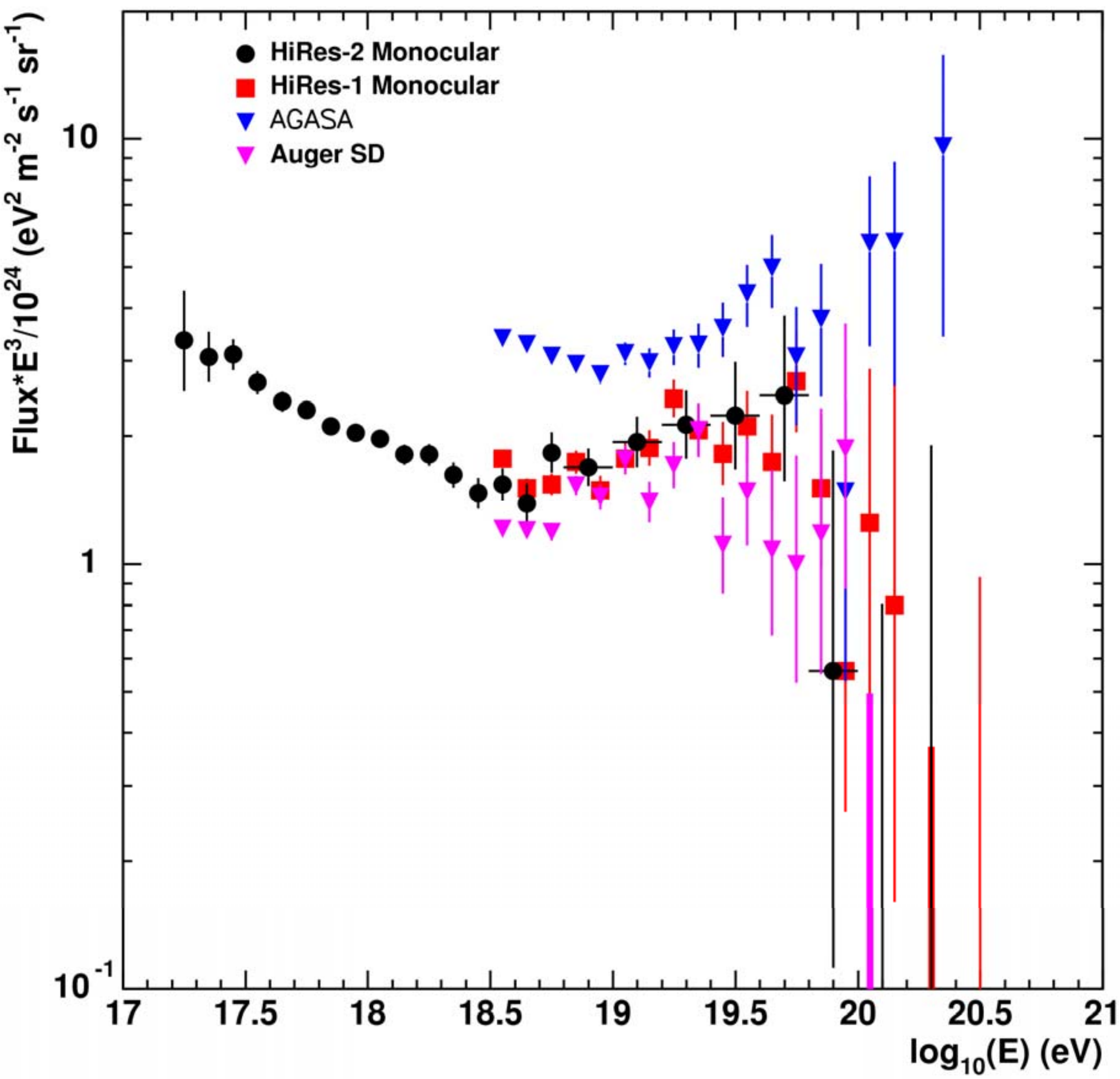
Spectrum

- **Comparison to AGASA and HiRes 1 monocular spectra**
- **No events above 10^{20} eV in energy spectrum, but 2 σ upper limit is consistent with AGASA flux**
- **With current systematics and statistics, solid conclusion is not possible *at this time***



29th ICRC Pune   S. Yoshida EHE CR rapporteur

Auger SD spectrum



- **Energy scale uncer. still large**
  - ~40 % in 100 EeV
  - improvement will come soon

Exposures:

HiRes1 (mono) ~5000 km2 sr yr

HiRes (Stereo) ~2500 km2 sr yr

Auger ~1750 km2 sr y~AGASA

Chiba University

Perdite d'energia (protoni)

Perdite d'energia legate a collisioni multiple con la radiazione cosmica di fondo

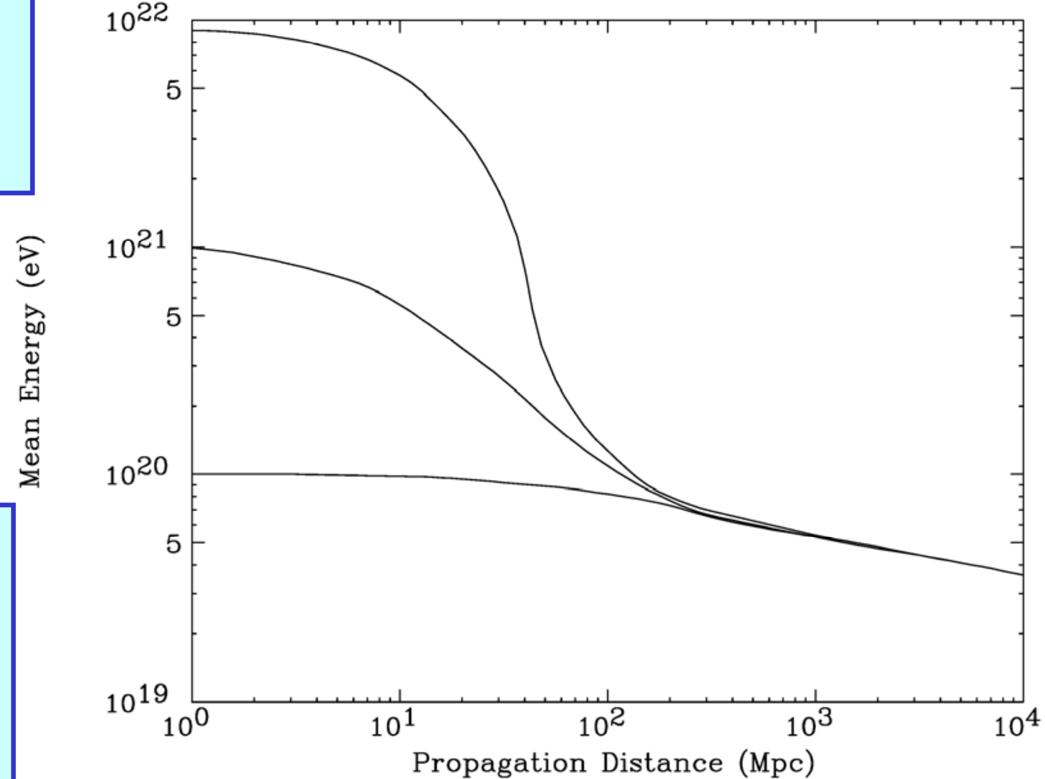


Figure 4: Mean energy of protons as a function of propagation distance through the CMB. Curves are for energy at the source of 10^{22} eV, 10^{21} eV, and 10^{20} eV.

Tali perdite d'energia sono soggette a importanti fluttuazioni (non Poissoniane)
Vedi figura successiva

Fluttuazioni in energia

Interazione "stocastica" in cui una frazione considerevole dell'energia puo` esser persa in una singola collisione

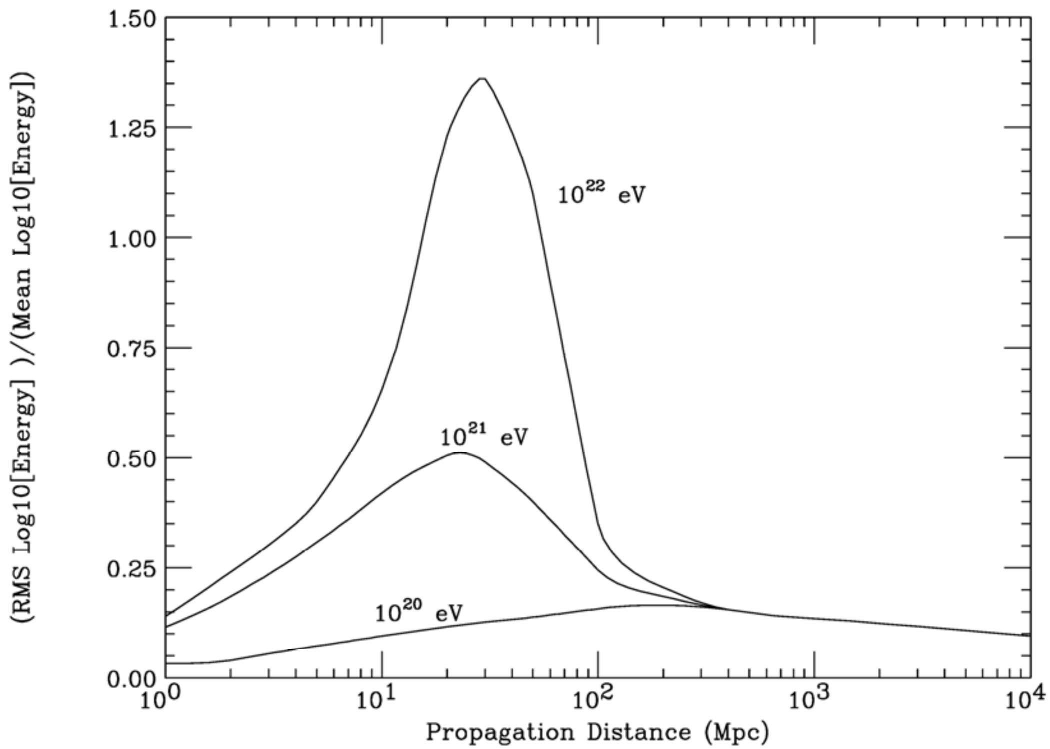


Figure 5: Fluctuation of the energy of a proton propagating through the CMB.

Probabilita'

Probabilita` che l'evento osservato ad una data energia abbia avuto origine ad una distanza maggiore di quella indicata sull'asse delle x

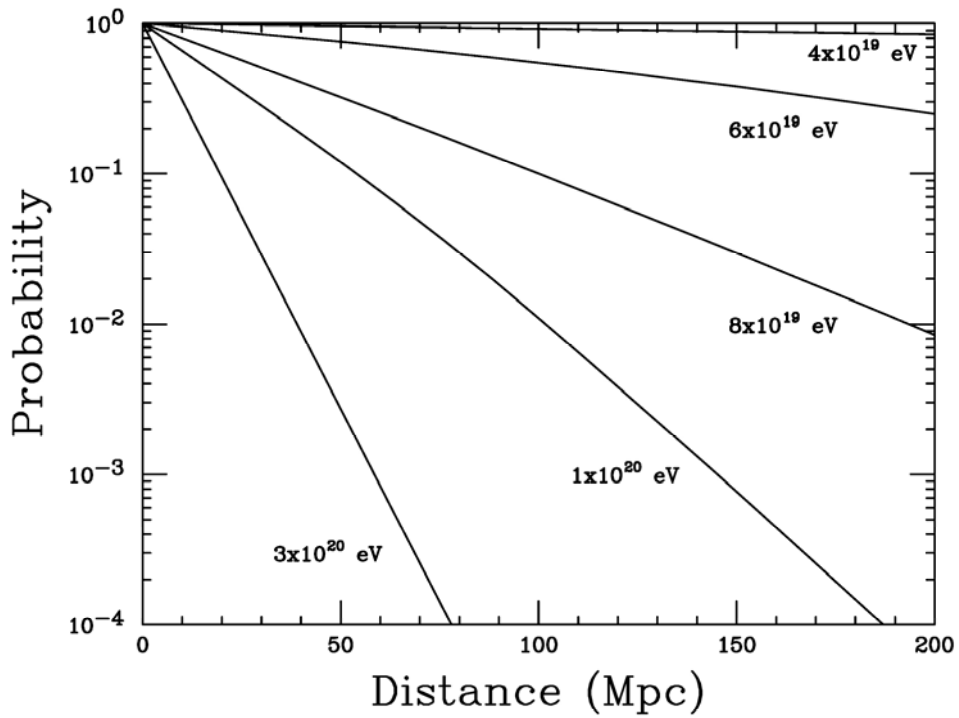
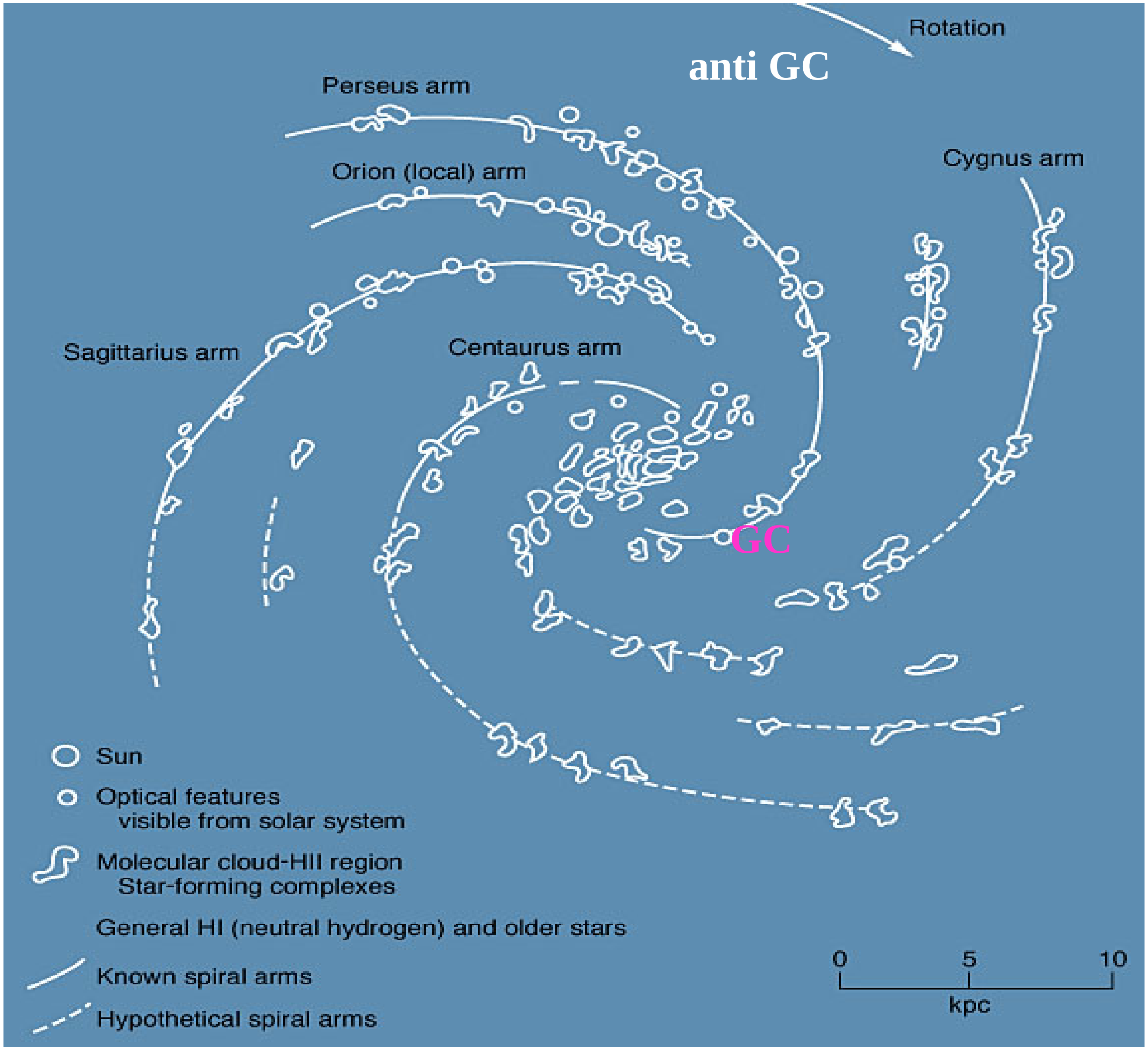


Figure 6: Probability that an observed event at a given energy has its source at a distance greater than the indicated distance. A source spectrum proportional to $E^{-2.5}$ is assumed. Figure provided Paul Sommers, University of Utah.

Galassia



Rotation
anti GC
Perseus arm
Cygnus arm
Orion (local) arm
Sagittarius arm
Centaurus arm
GC
Sun
Optical features
visible from solar system
Molecular cloud-HII region
Star-forming complexes
General HI (neutral hydrogen) and older stars
Known spiral arms
Hypothetical spiral arms
0
5
10
kpc

Galassia

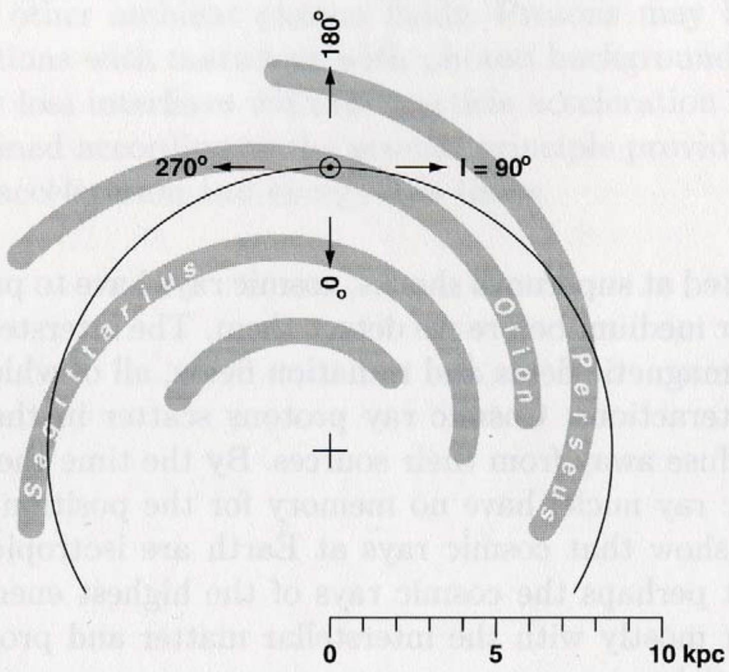


Fig. 4.2. View of the Galaxy from its North Pole. The galactic center is indicated with a cross. The galactic longitude ℓ is shown with arrows. The thin circle shows the solar circle.

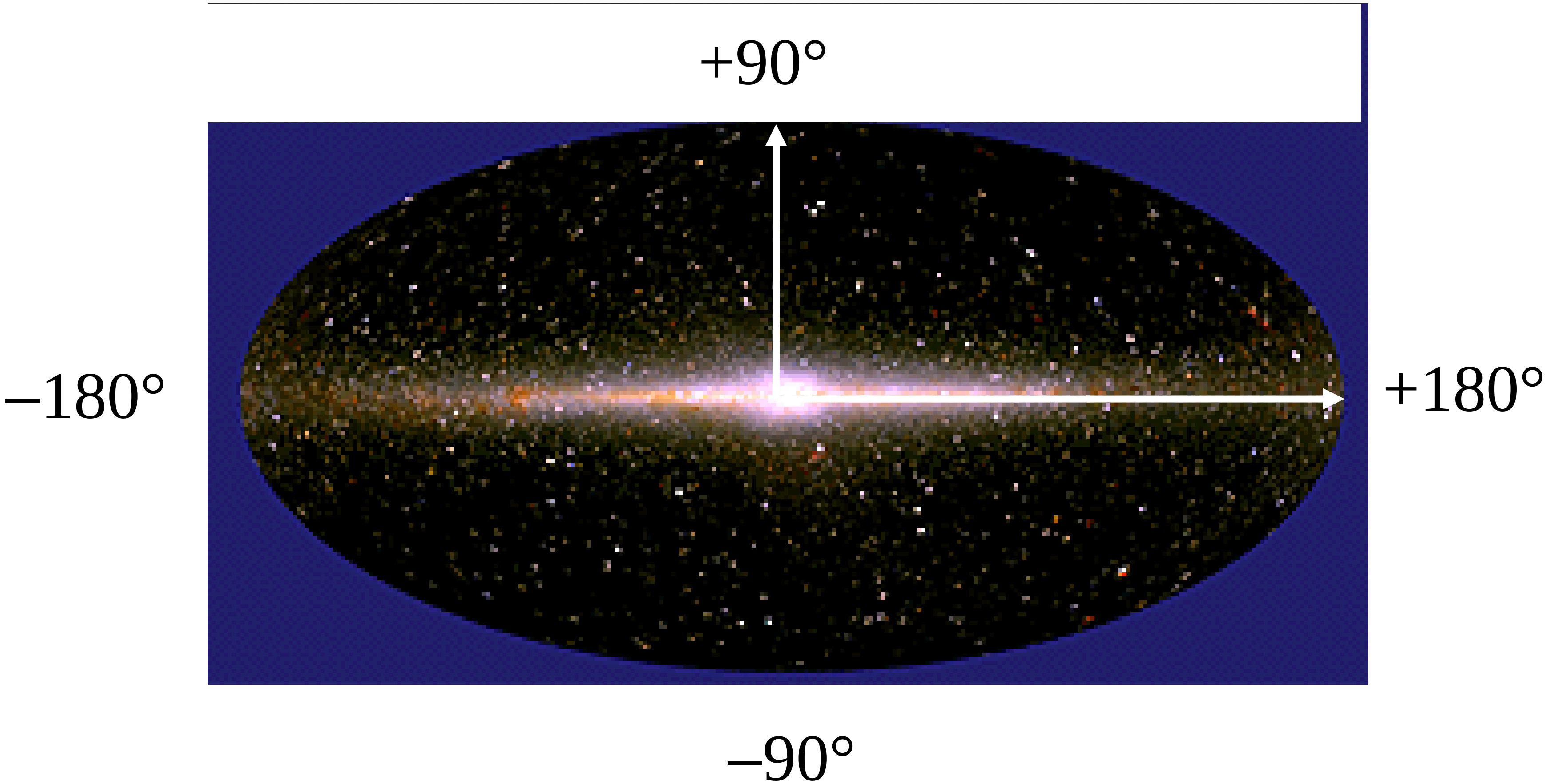
1 parsec (pc) = distanza dalla quale il raggio dell'orbita terrestre e' visto sotto l'angolo di 1"

Anno luce (A.L.) → $9{,}4605 \times 10^{12}$ km

1 A.L. = 0,3066 pc

1 pc = 3,262 A.L.

Latitudine galattica



Campo magnetico galattico

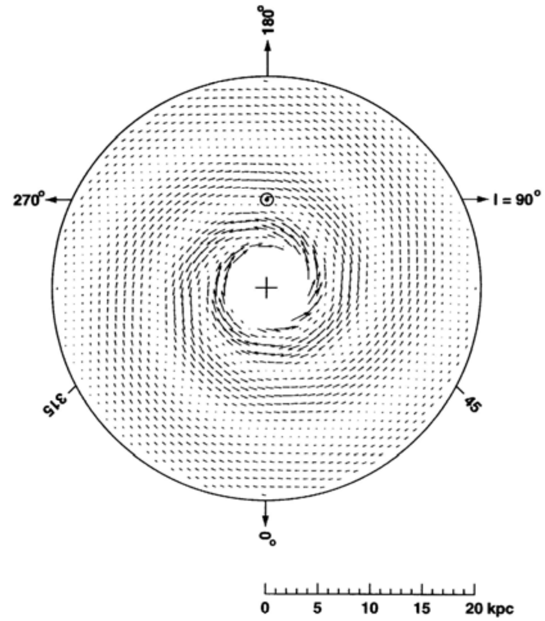


Fig. 4.4. Magnetic field strength (length of arrows) and direction in the galactic plane for the BSS model [76]. The field reversals can be best seen close to the galactic center where the field values are higher. The field is not plotted within 4 kpc of the galactic center because of the very high uncertainty in this region. The positions of the galactic center and the solar system are indicated.

Modello bisimmetrico:

$$B(r,\phi) = B_0(r)\cos\left(\phi - \beta \ln\frac{r}{r_0}\right)$$

r_0 = distanza della posizione del massimo di B dal centro della Galassia (10.55 kpc)

$\beta = 1/\tan p$ (p - angolo di "pitch" della spirale = -10^0)

$B \approx 2\mu G$ in prossimita' del sistema solare

Effetto del campo

Effetto del campo magnetico galattico/extragalattico

Raggio di Larmor di una particella di numero atomico Z:

$$\rho(Mpc) = 1.08 \times 10^{2}\ (E/10^{20}\,eV)(1/B_{nG})(1/Z)$$

e.g. protone di 10^{19} eV nel campo galattico di 1 μG → ρ = 10 kpc; maggiore dello spessore del disco galattico → se nato nella galassia, non vi rimarra'
Nuclei piu' pesanti (Z maggiore) sarebbero confinati piu' a lungo

→ origine extragalattica ?

Traiettorie *(proiettate sul piano normale alla direzione di propagazione)*

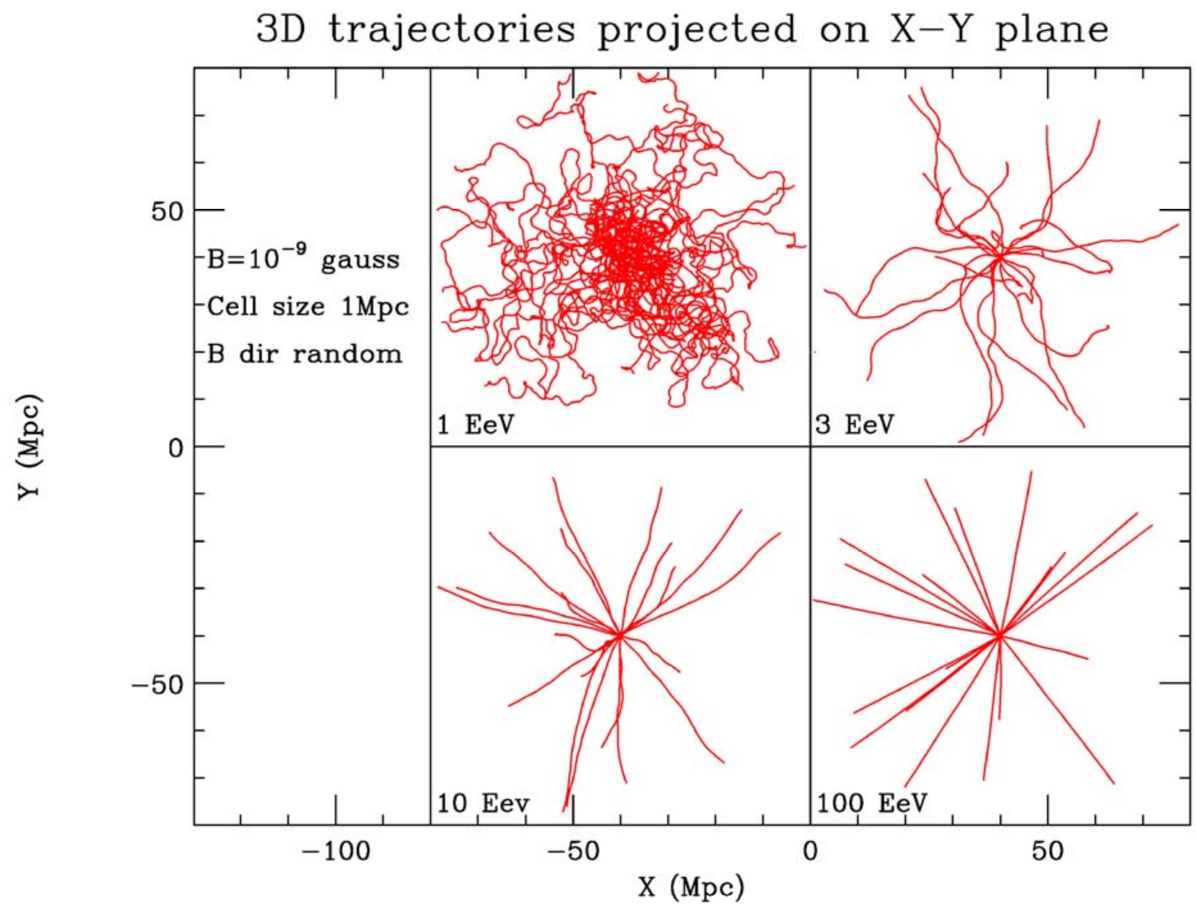


Figure 7: Projected view of 20 trajectories of proton primaries emanating from a point source for several energies. Trajectories are plotted until they reach a physical distance from the source of 40Mpc. See text for details.

Effetto sull'angolo

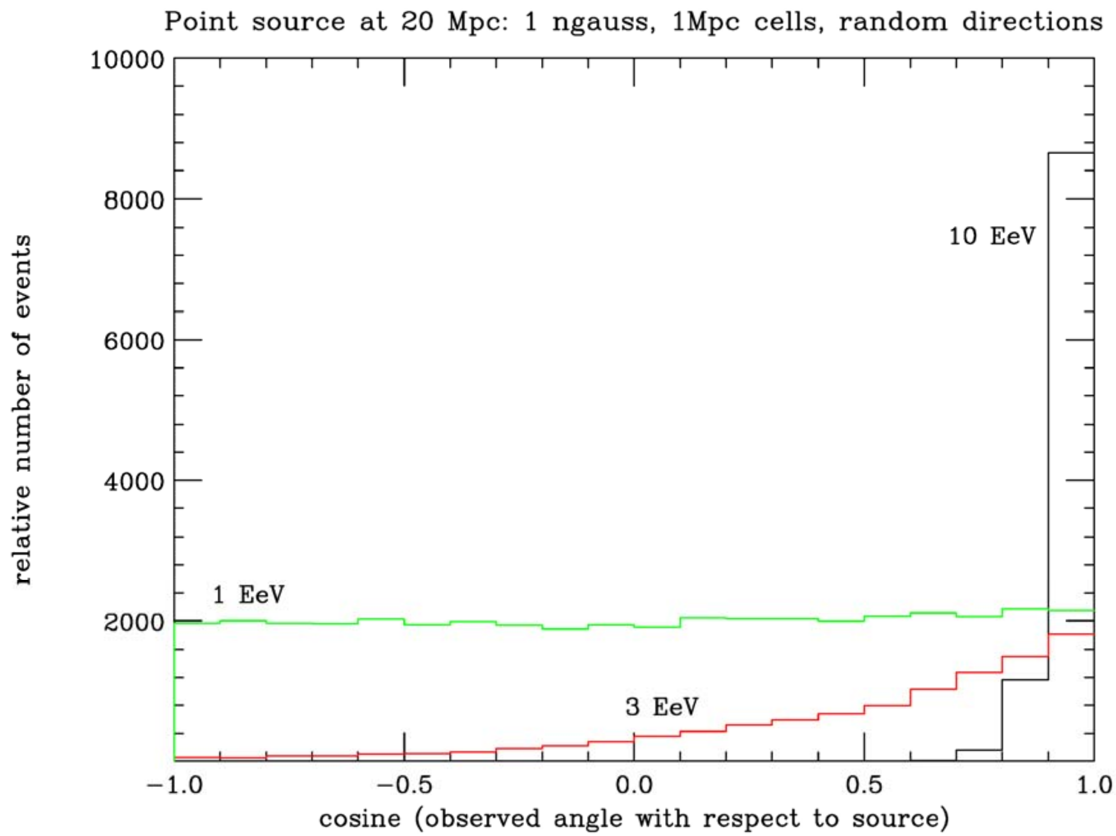


Figure 8: Distribution at 20 Mpc distance of the observed cosmic ray angle with respect to the source direction for proton primaries at the indicated energies.

Effetto sull'angolo (alte energie)

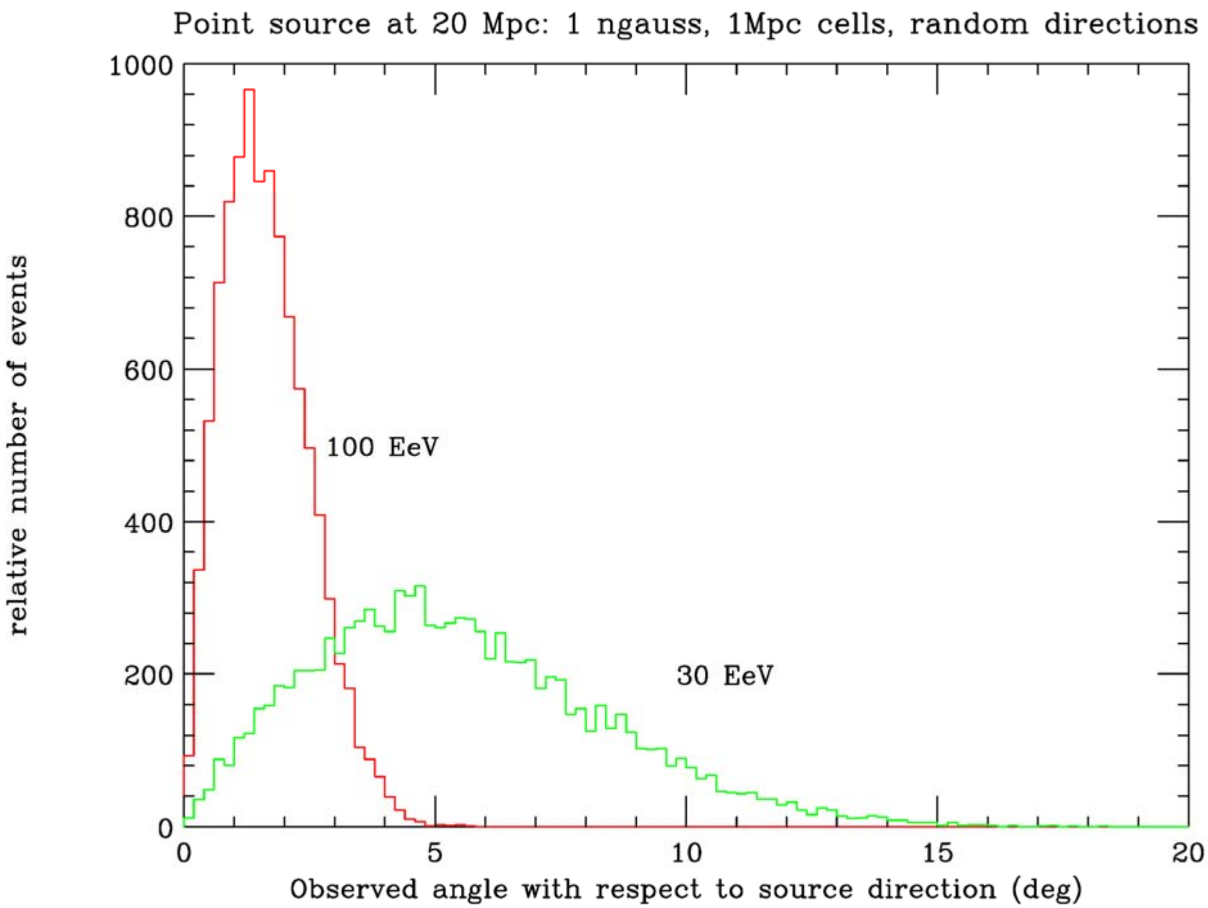


Figure 9: Distribution at 20 Mpc distance of the observed cosmic ray angle with respect to the source direction for proton primaries for the cases of small deflection.

Sorgenti extragalattiche ?

Dove sono le possibili sorgenti extragalattiche ?

Distribuzione della materia (7-21 Mpc)

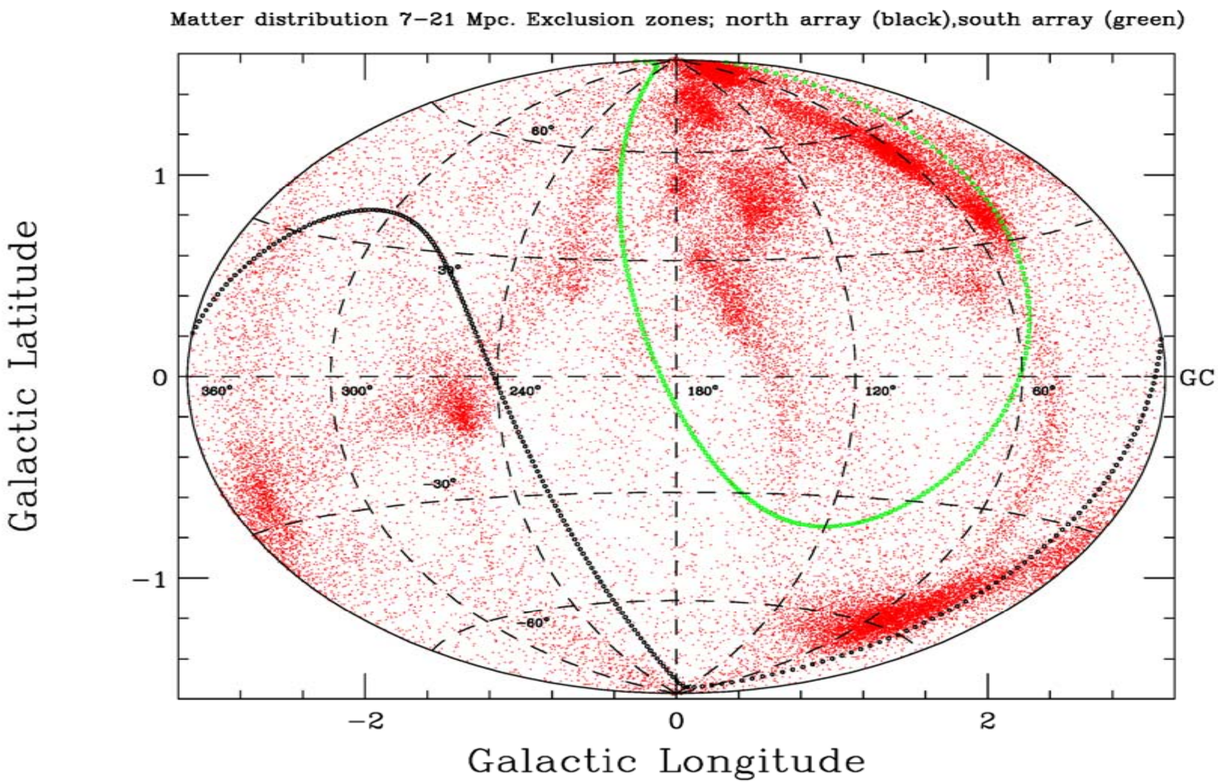


Figure 10: Distribution in galactic coordinates of gravitating matter at distance between 7 and 21 Mpc. The density of dots in the figure is proportional to the column density of the matter in the interval. The exclusion zones are plotted for a zenith angle $\leq$ 60deg. On the left is the exclusion zone for a northern observatory, on the right for a southern observatory. An observatory in the southern hemisphere will not see directly the Virgo cluster. (The data were provided by Andrey Kravtsov, Center for Cosmological Physics, University of Chicago).