Cosmic Ray Physics, overview

Next: CR’s are out there; how do we detect them?

Two Basic Approaches:

A) Stuck on Earth:

1) Identify the CR primary particle you’re most interested in
2) Identify the energy range that you’re most interested in for that CR
3) Look up the interaction cross-section of that CR, at that E, with matter (air, e.g.)
4) Figure out decay products (aka, `secondaries’)
5) Determine layout of an experiment designed to detect the maximum number of secondaries

B) Out in space:

1) No atmospheric target => detect primary directly!

What science do CR detectors target?

Emphasis on answering three basic questions:

1) How well can we define the composition of the *primary* cosmic ray particles incident on Earth from the secondaries?

  - What is the relative abundance of protons vs. gammas vs. heavy (not Hydrogen) nuclei?

2) What is energy 'spectrum' (dN/dE) and what does that tell us about how the CR's are generated?

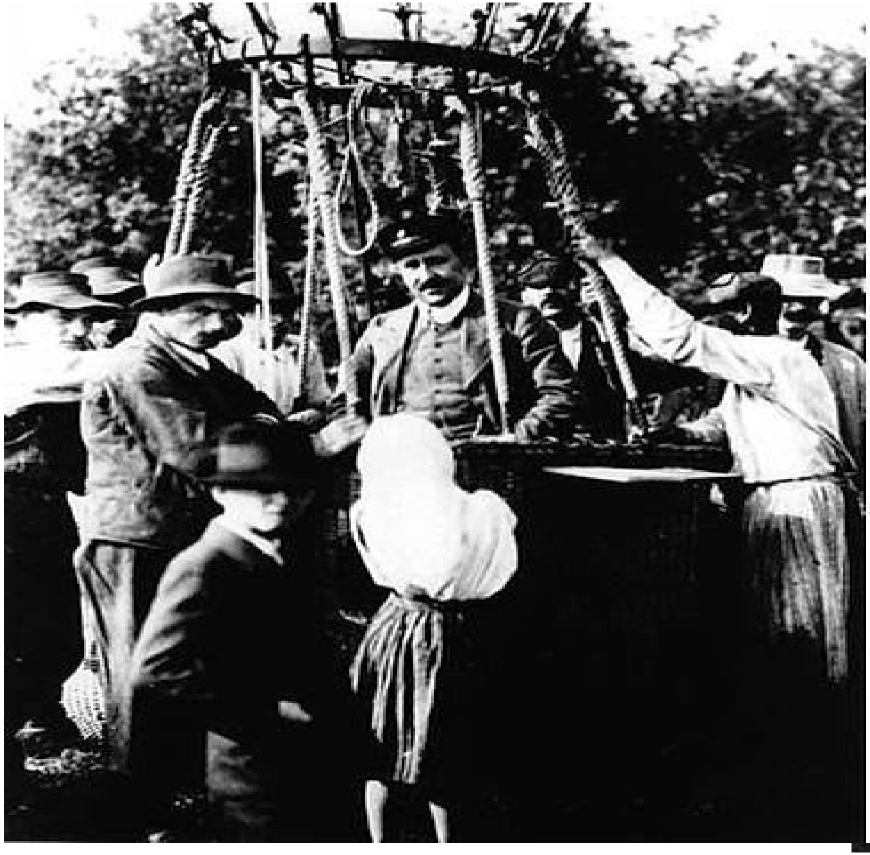
  - e.g., $dN/dE \sim E^{-\gamma}$: "power law"=>shock traversal

    γ: "spectral index"

    - or could have multiple spectral indices=>multiple processes

3) What is the angular distribution of the CR we measure, and do they point back (i.e., `cluster') to sources?

In the beginning (while RF Scott et al were ice-locked in a tent)



Victor Hess (April, 1912, Austrian [Fordham U, 1938]): 1) Ionization increases with altitude 2) Ascent during solar eclipse shows that sun is not source

Measure discharge of Wulf Electroscope

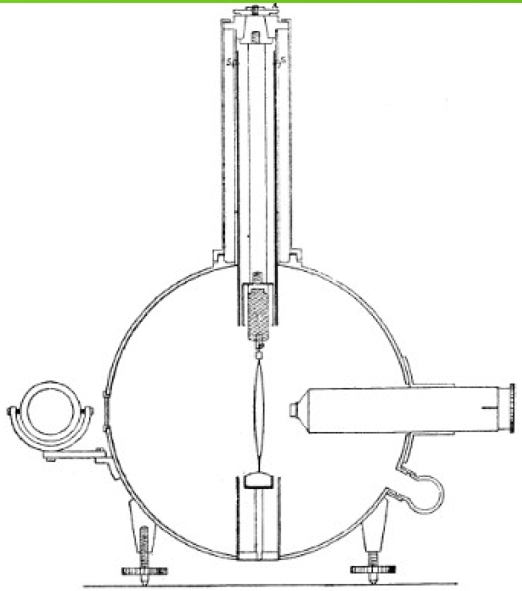
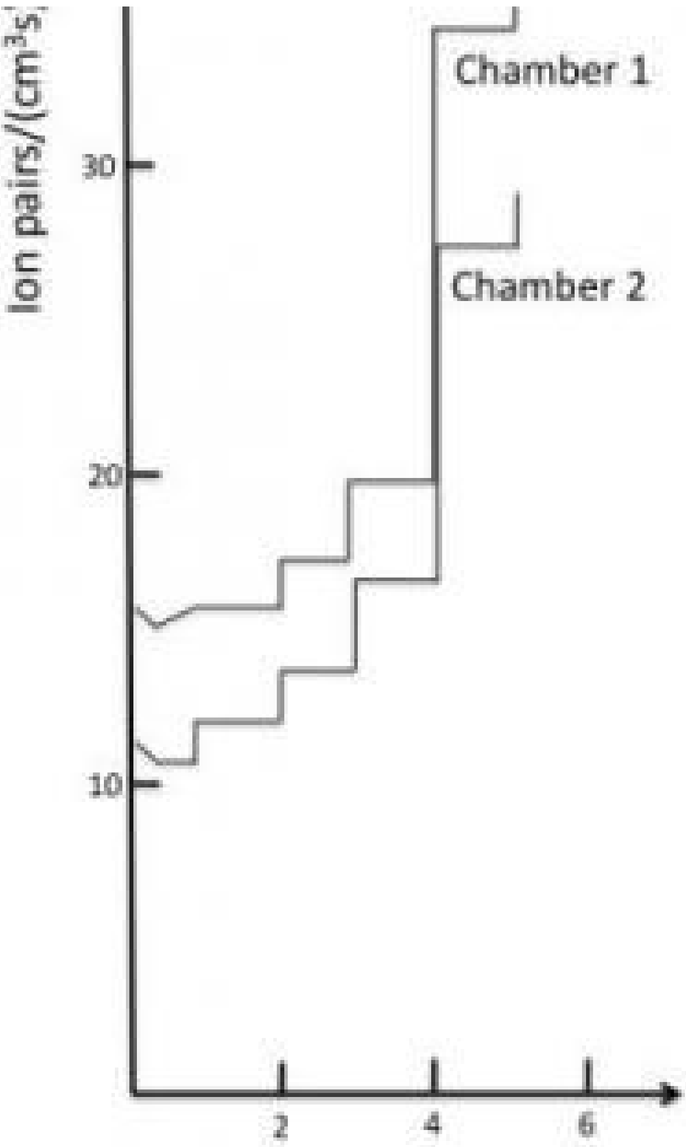
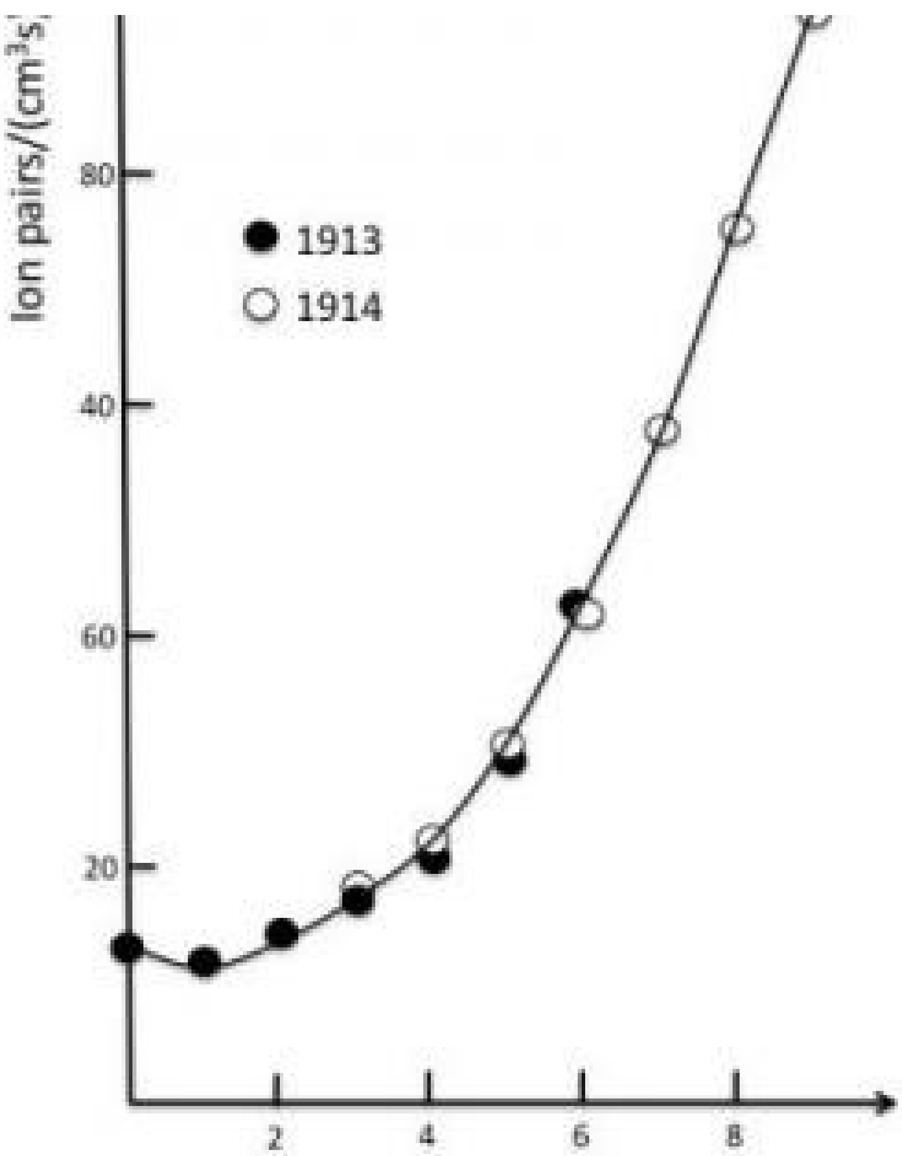


Figure 1: The Wulf electroscope. The 17 cm diameter cylinder with depth 13 cm was made of Zinc. To the right is the microscope that measured the distance between the two silicon glass wires illuminated using the mirror to the left. The air was kept dry using Sodium in the small container below the microscope. According to Wulf [16], with 1.6 ion pairs per second produced, the tension was reduced by 1 V, the sensitivity of the instrument, as measured by the decrease of the inter-wire distance.



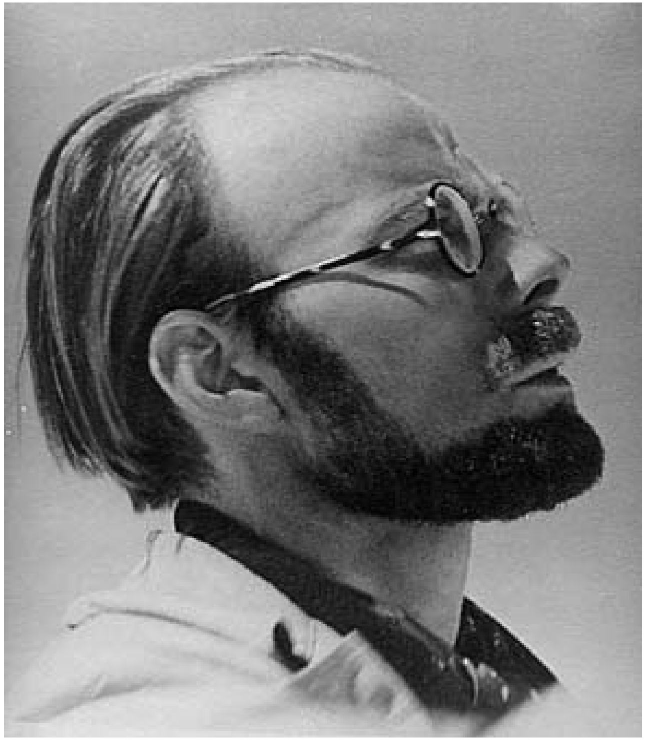
Ion pairs/(cm³s)
30
20
10
Chamber 1
Chamber 2
2
4
6



Ion pairs/(cm³s)
80
40
60
20
1913
1914
2
4
6
8

Pierre Auger (1937, French)

Detection of Extensive Air Showers via coincidence measurements



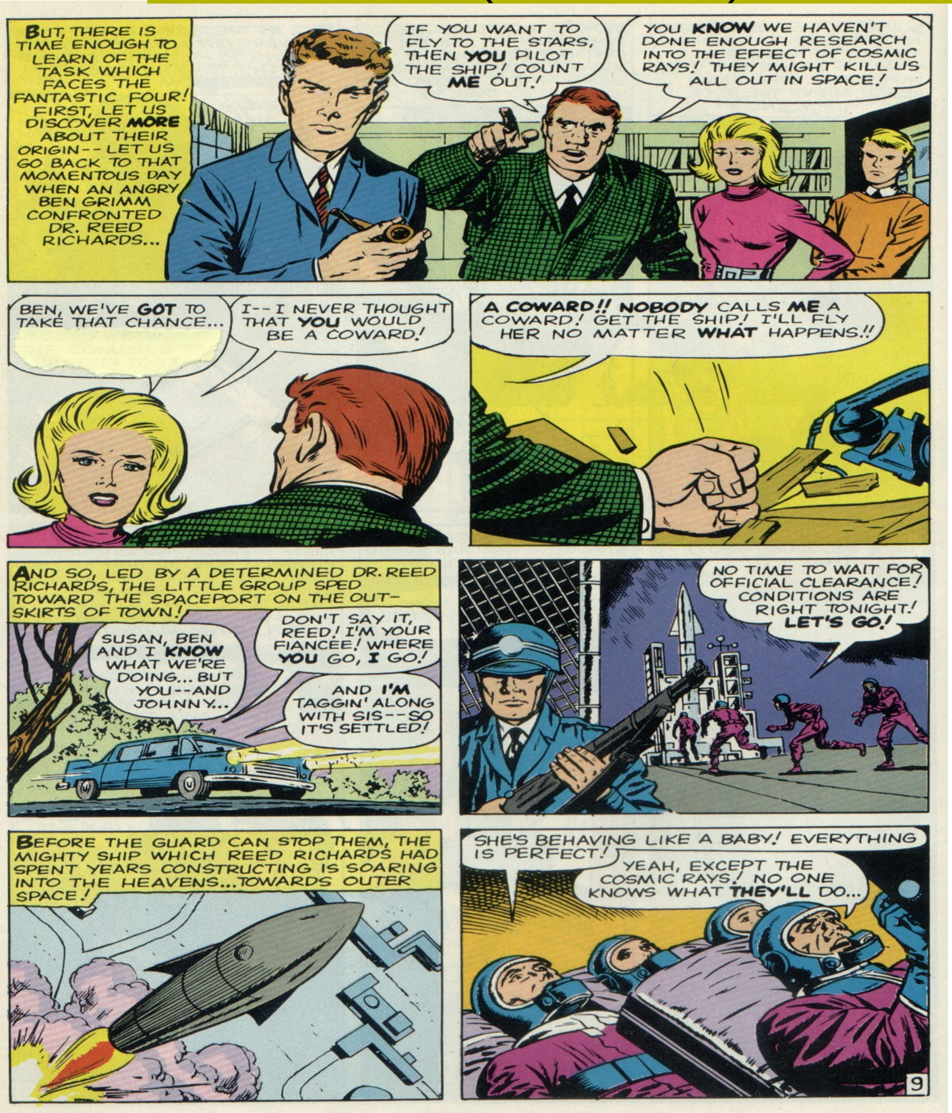
“Too small to touch, taste, smell, or feel...”

JULY-OCTOBER, 1939 REVIEWS OF MODERN PHYSICS VOLUME 11

Extensive Cosmic-Ray Showers

PIERRE AUGER
In collaboration with
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
Paris, France

Reed Richards (1961, **USA**) – The American approach

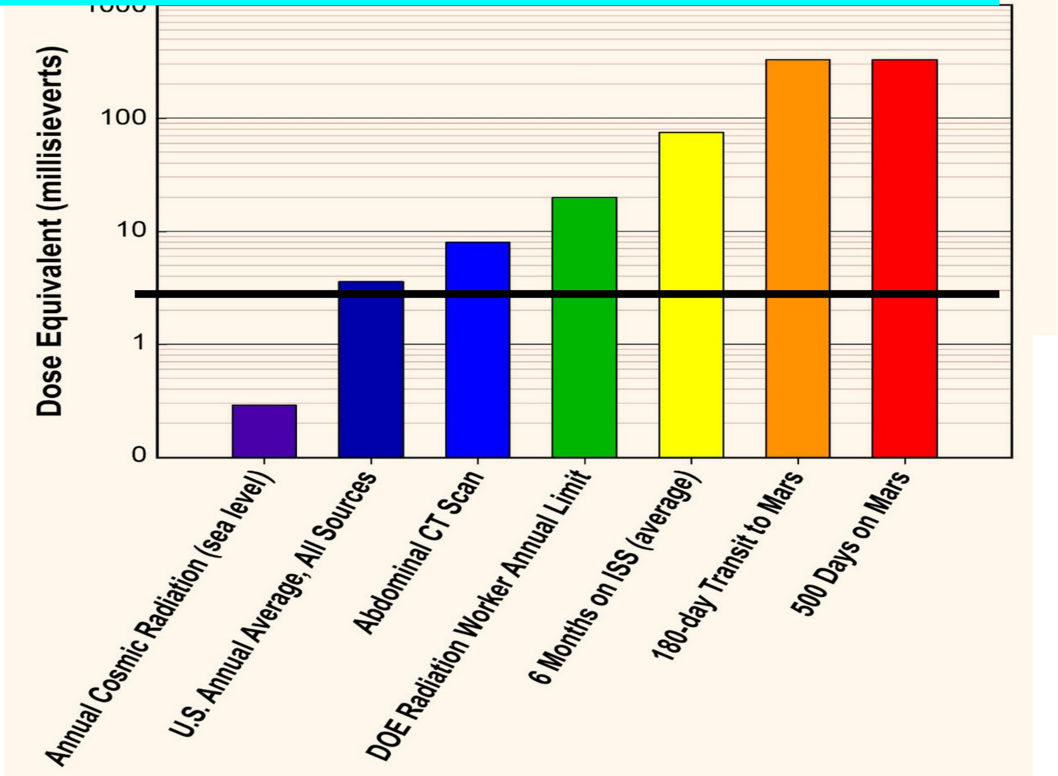


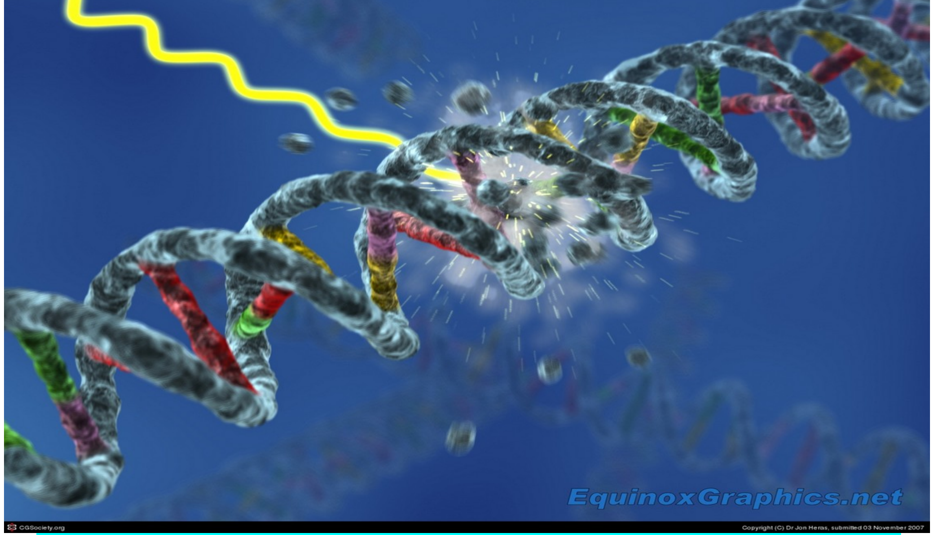

YOU'VE TURNED INTO MONSTERS... BOTH OF YOU!! IT'S THOSE RAYS! THOSE TERRIBLE COSMIC RAYS!
NOW I KNOW WHY I'VE BEEN FEELING SO WARM! LOOK AT ME!! THEY'VE AFFECTED ME, TOO! WHEN I GET EXCITED I CAN FEEL MY BODY BEGIN TO BLAZE!
I'M LIGHTER THAN AIR!! I CAN FLY!! LOOK... I CAN FLY!!
MINUTES LATER, JOHNNY STORM'S FLAME SUBSIDED AND HE LANDED NEAR THE OTHER THREE! SILENTLY THEY WATCHED THE SMALL FIRE HE HAD STARTED IN THE UNDERBRUSH BURN ITSELF OUT!! SILENTLY THEY WERE EACH OCCUPIED WITH THEIR OWN STARTLING THOUGHTS!
WE'VE CHANGED! ALL OF US! WE'RE MORE THAN JUST HUMAN!
LISTEN TO ME, ALL OF YOU! THAT MEANS YOU TOO, BEN! TOGETHER WE HAVE MORE POWER THAN ANY HUMANS HAVE EVER POSSESSED!
YOU DON'T HAVE TO MAKE A SPEECH, BIG SHOT! WE UNDER-STAND! WE'VE GOTTA USE THAT POWER TO HELP MANKIND, RIGHT?
RIGHT, BEN, RIGHT!
I'M CALLING MYSELF THE HUMAN TORCH-- AND I'M WITH YOU ALL THE WAY!
SAME GOES FOR ME... THE INVISIBLE GIRL!
THERE'S ONLY ONE STILL MISSING... BEN!!
I AIN'T BEN ANYMORE-- I'M WHAT SUSAN CALLED ME-- THE THING!!
AND I'LL CALL MYSELF... MISTER FANTASTIC!!
AND SO WAS BORN "THE FANTASTIC FOUR!!" AND FROM THAT MOMENT ON, THE WORLD WOULD NEVER AGAIN BE THE SAME!!
13
15


THE INCREDIBLE HULK
ULTIMATE DESTRUCTION
™

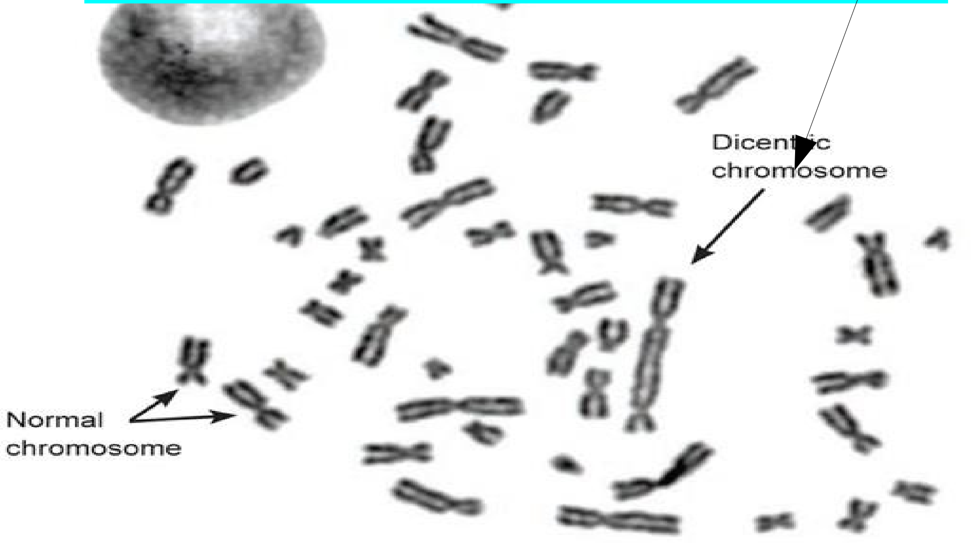
Practical consequences: Cancer rates in airline pilots x2 general population

Bush proposal to send man to Mars (2004)





ISS astronaut blood cells



A. Niger thrives in radiation environments! Why? KUbeSat project (launch 2020): astrobiology

Space station mold survives 200 times the radiation dose that would kill a human

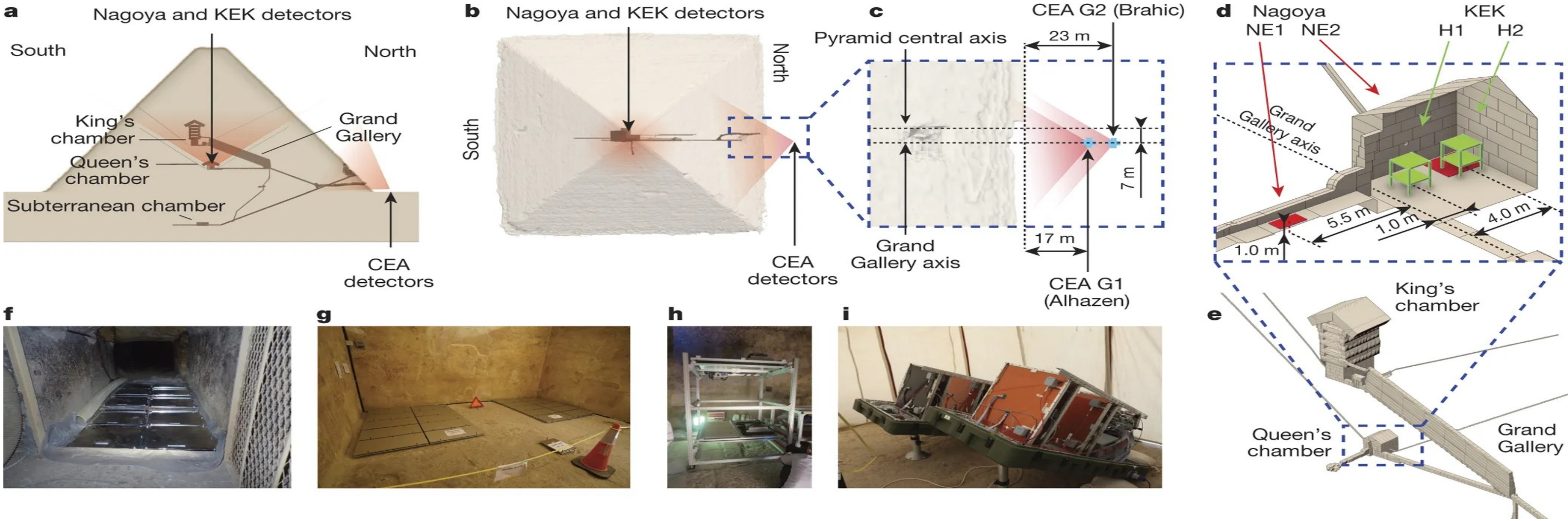
By Richard A. Lovett | Jun. 28, 2019 , 8:05 PM

nature

Letter | Published: 02 November 2017

Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons

Kunihiro Morishima, Mitsuaki Kuno, […] Mehdi Tayoubi



Cosmic Rays in Everyday life

Runaway Breakdown and the Mysteries of Lightning

The observed electric fields in thunderclouds are generally too weak to initiate the atmosphere's electrical breakdown. But cosmic rays can play a surprising role in the drama of lightning.

Alexander V. Gurevich and Kirill P. Zybin

Primer on Cosmic Rays in Everyday life

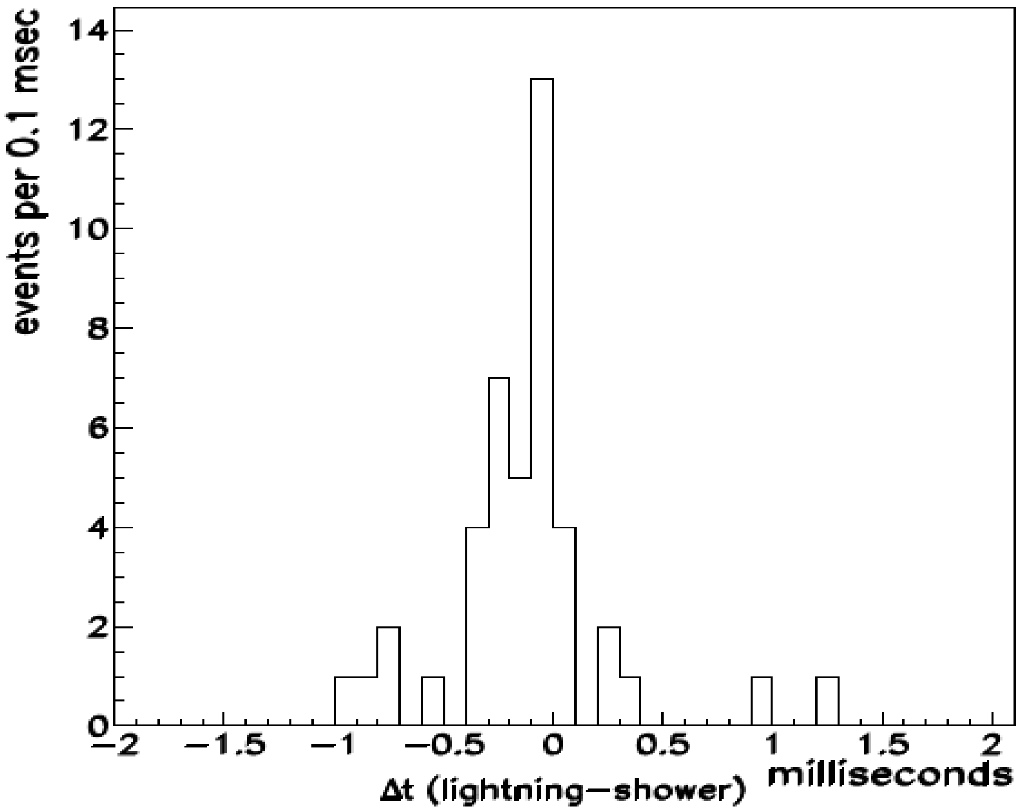
Runaway Breakdown and the Mysteries of Lightning

The observed electric fields in thunderclouds are generally too weak to initiate the atmosphere's electrical breakdown. But cosmic rays can play a surprising role in the drama lightning.

Alexander V. Gurevich and Kirill P. Zybin

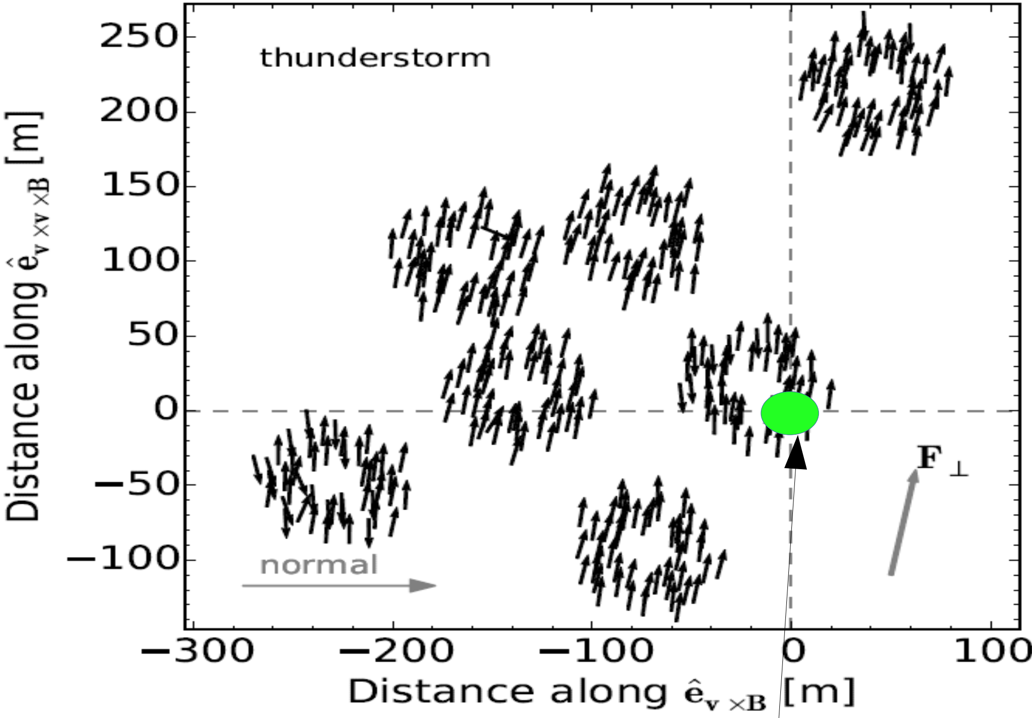
Greensburg, KS, June 7, 2011

Lightning Detection at the Telescope Array Cosmic Ray Observatory



Time Difference (in milliseconds) between registration of cosmic ray and lightning strike

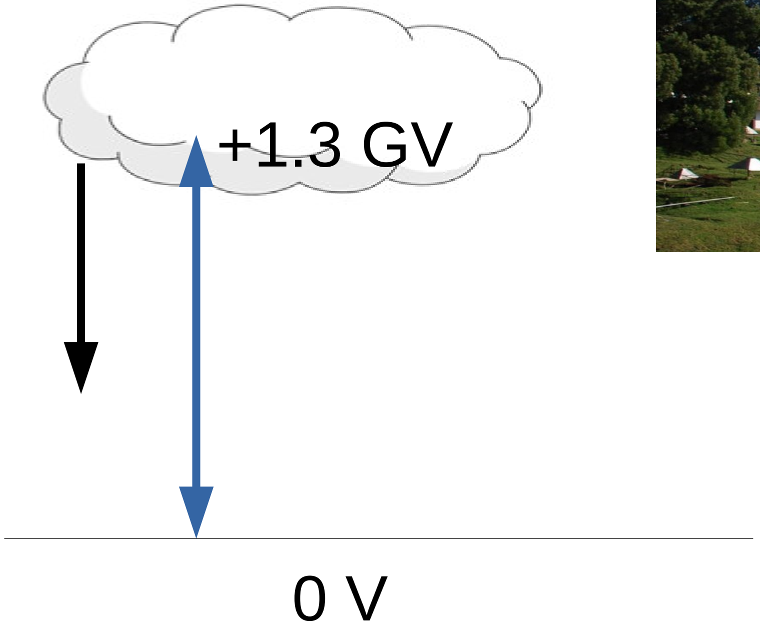
LOFAR measured Rx polariztion

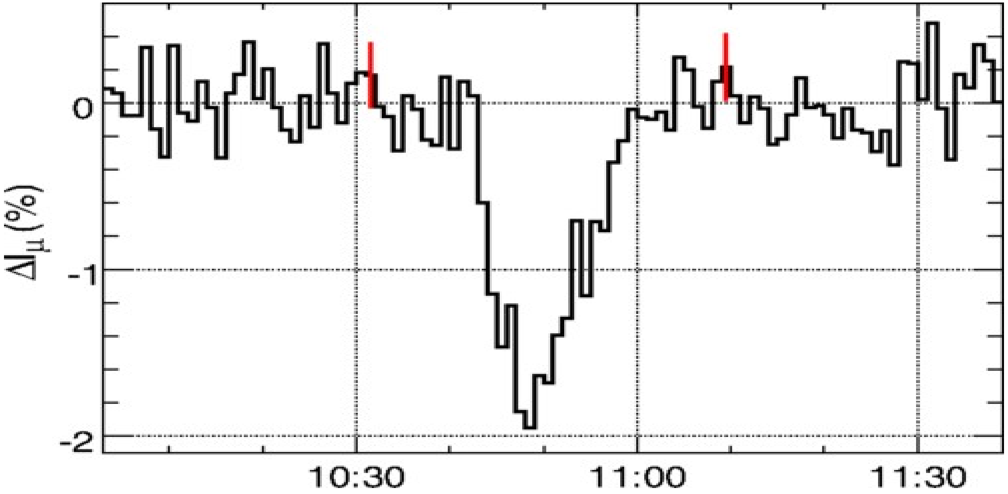


Location of shower core

GRAPES-3 measured $V_{thundercloud}$!

2014-12-01: GRAPES-3 (Gamma Ray Astronomy PeV EnergieS phase-3; Ooty) measures 1.3 gigaVolt thundercloud potential!

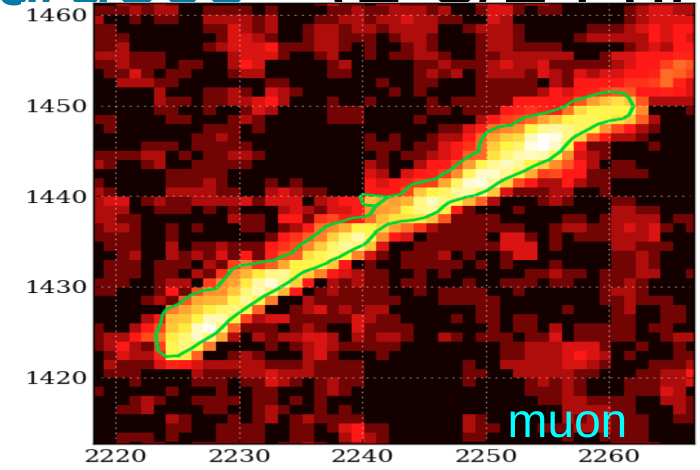


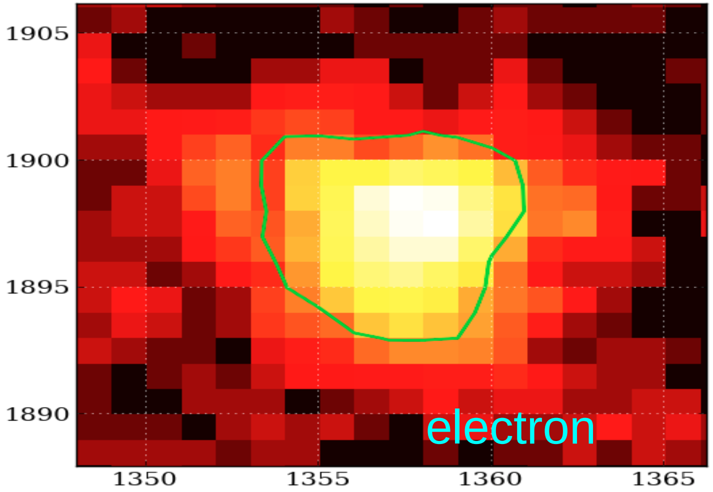


Negative muons with KE<1.3 GeV don't reach ground!

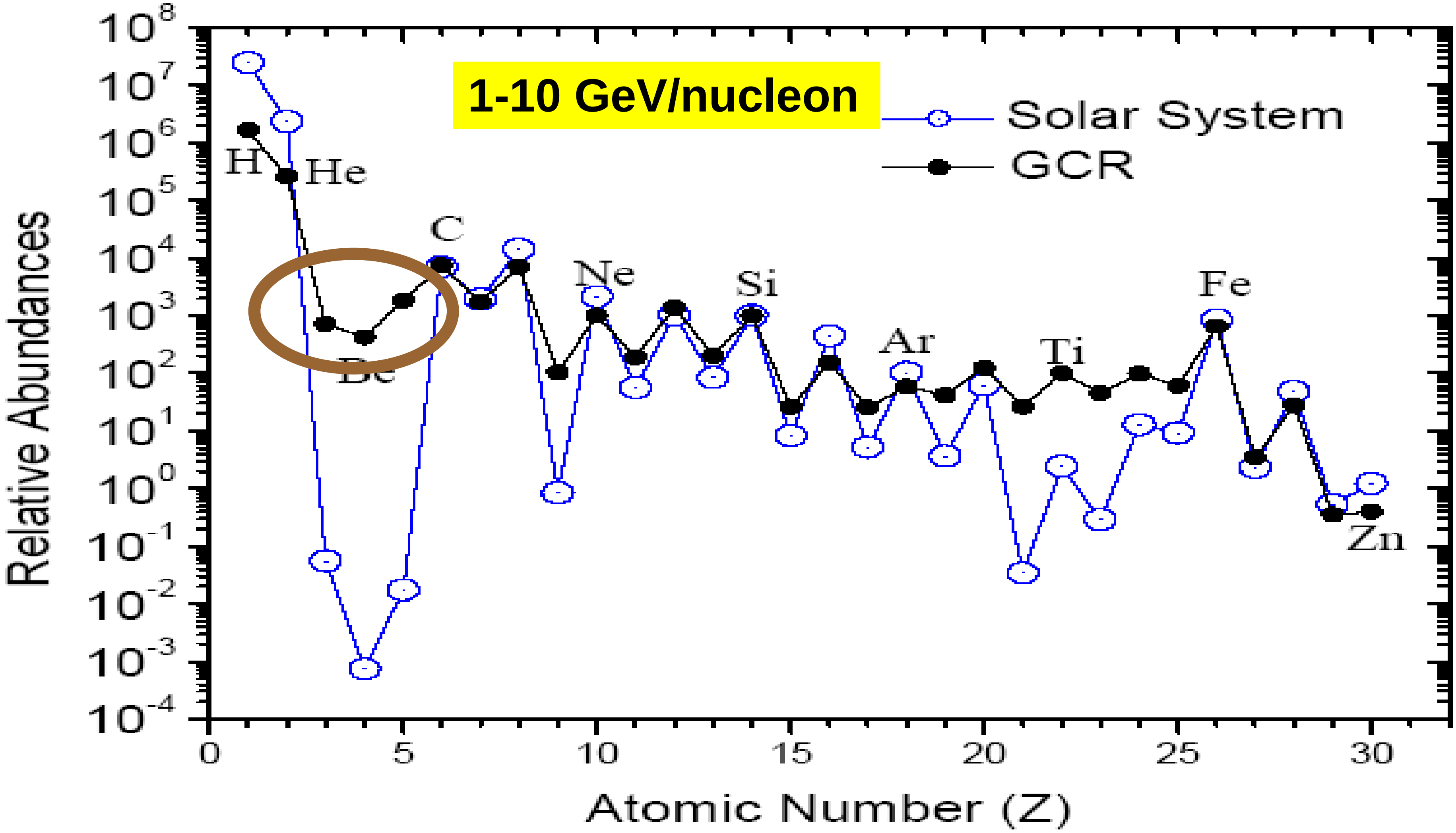
Your smartphone camera is a CR detector

- http://wipac.wisc.edu/deco - (2-3/24 hrs)

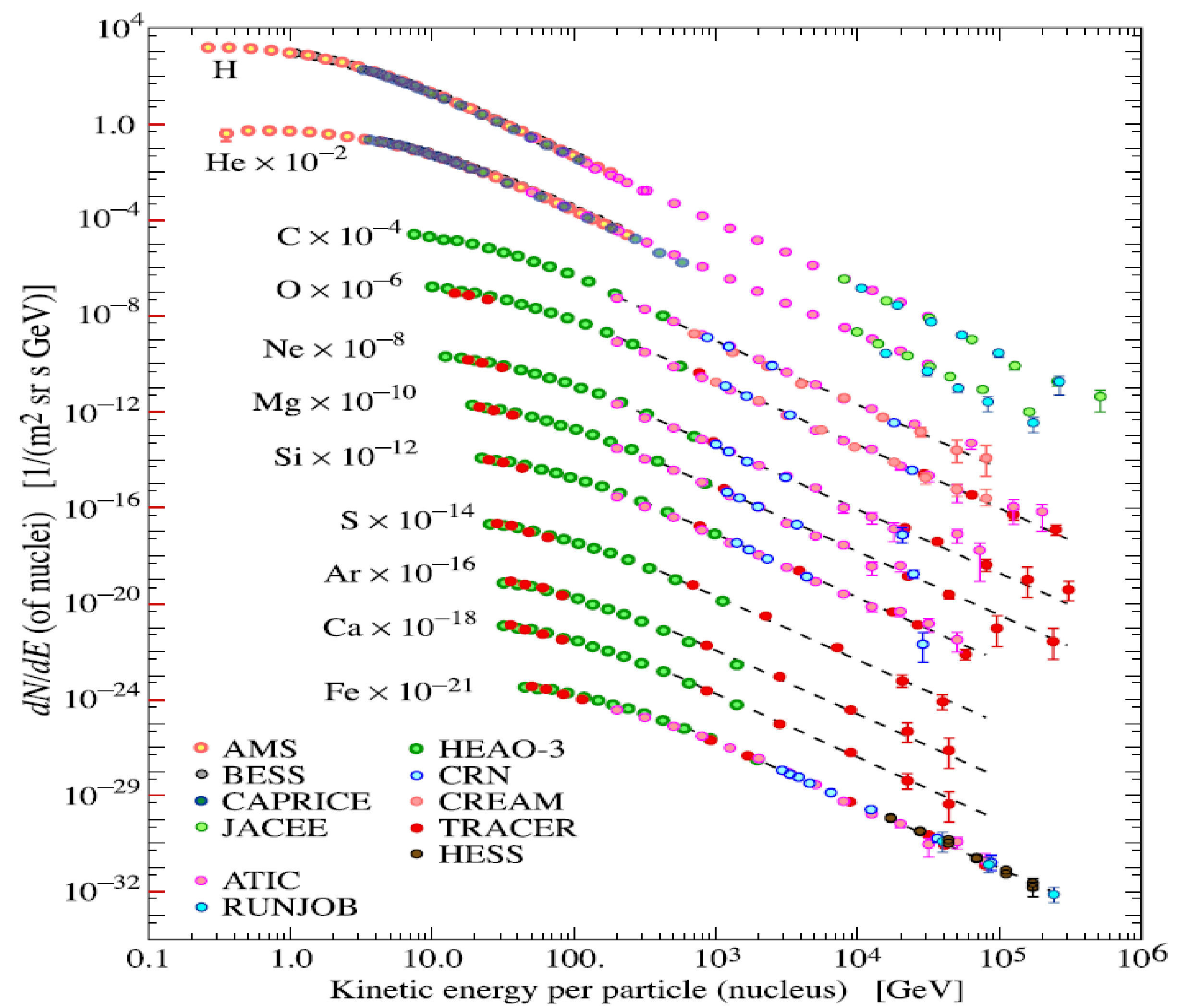


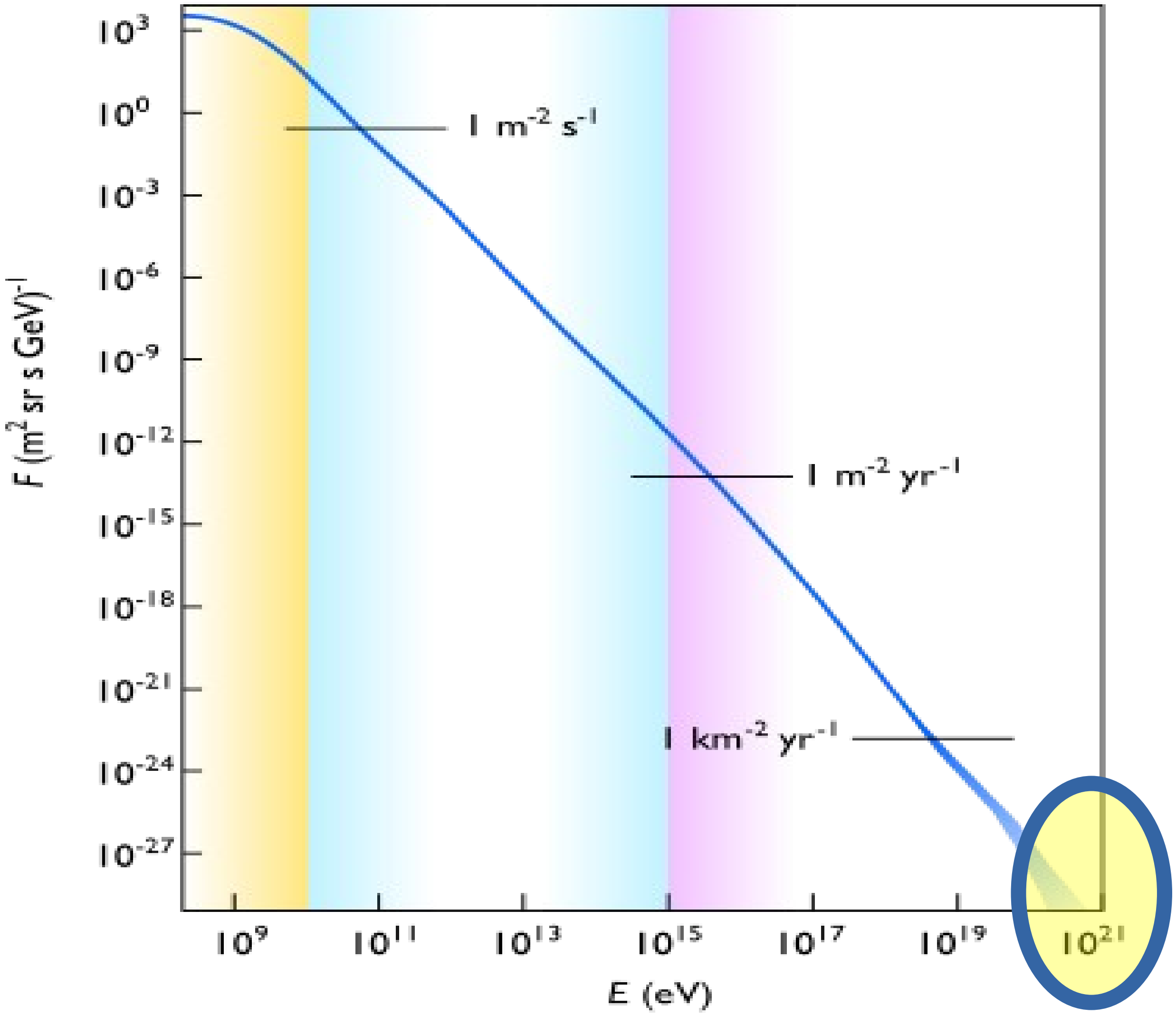


What is the cosmic ray abundance on planet Zolar?



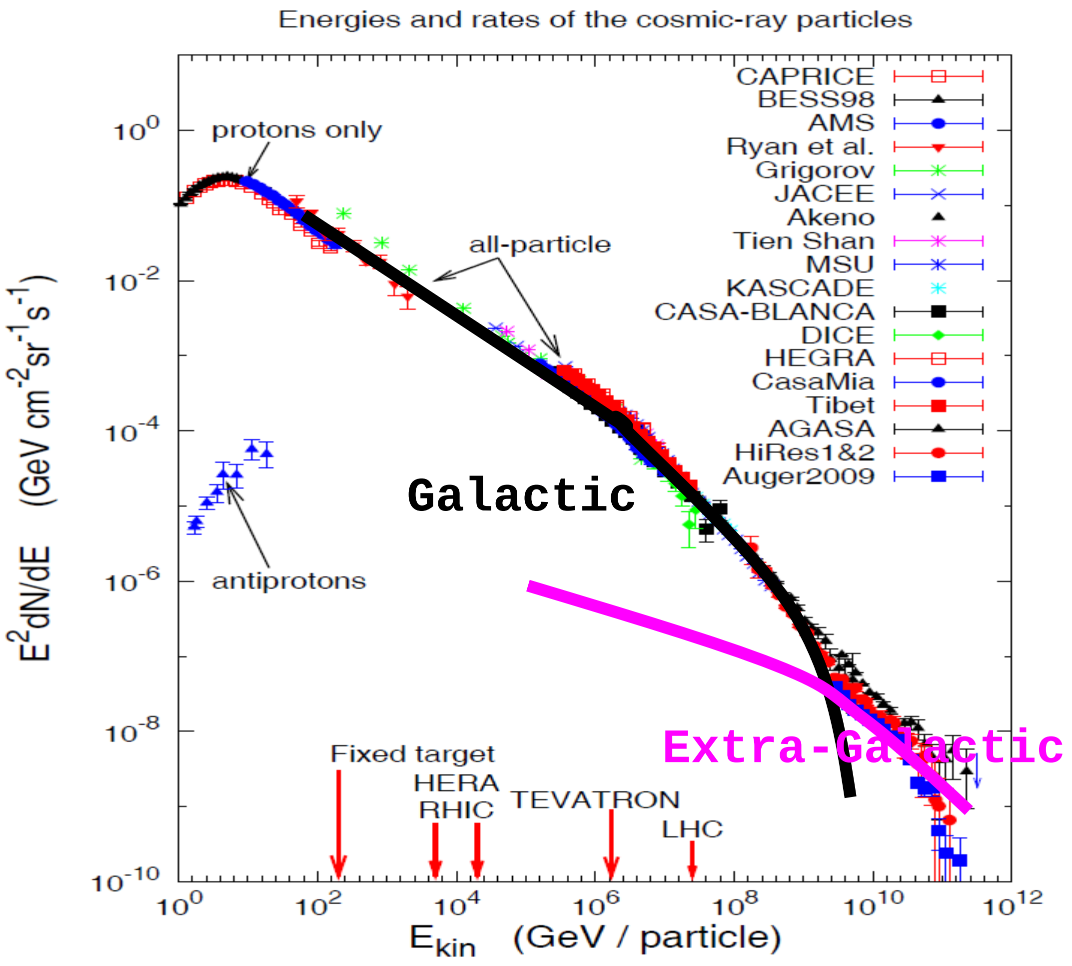
Energy spectrum of various CR nuclei



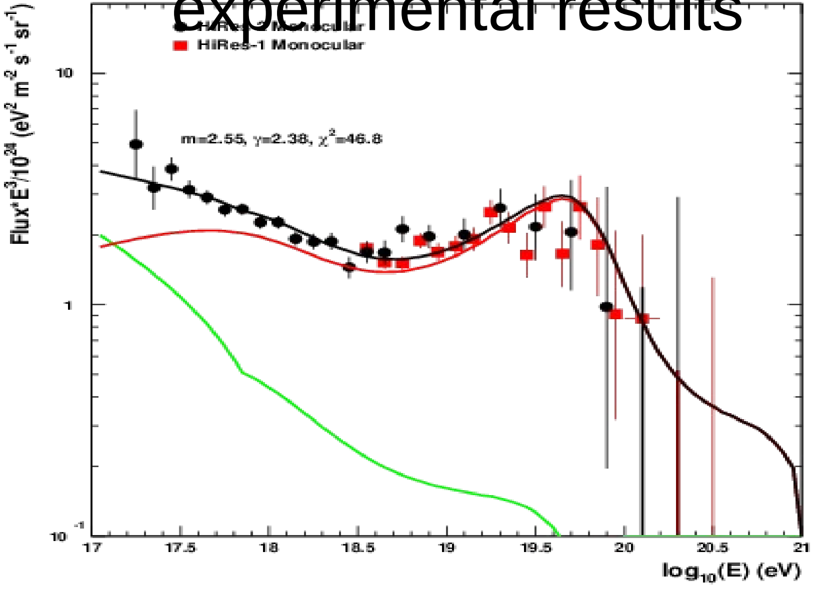


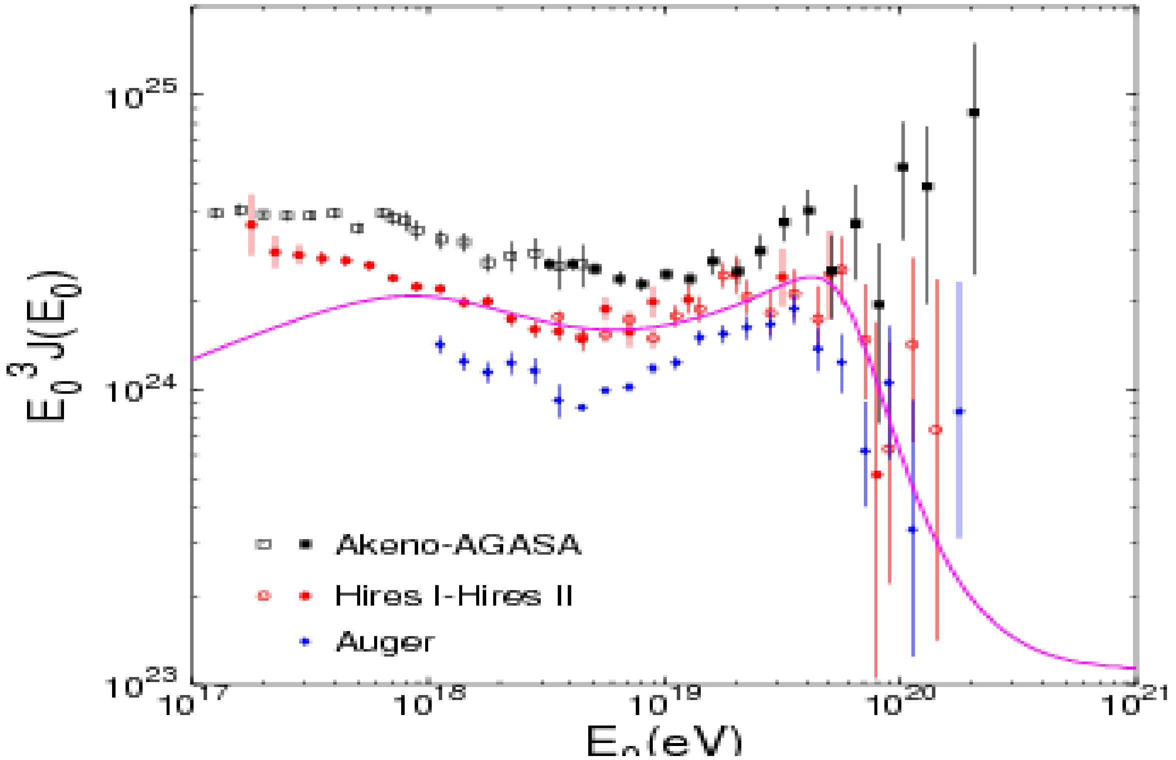
The charged cosmic ray energy spectrum at Earth, and GZK-cutoff

Galactic vs. Extragalactic sources

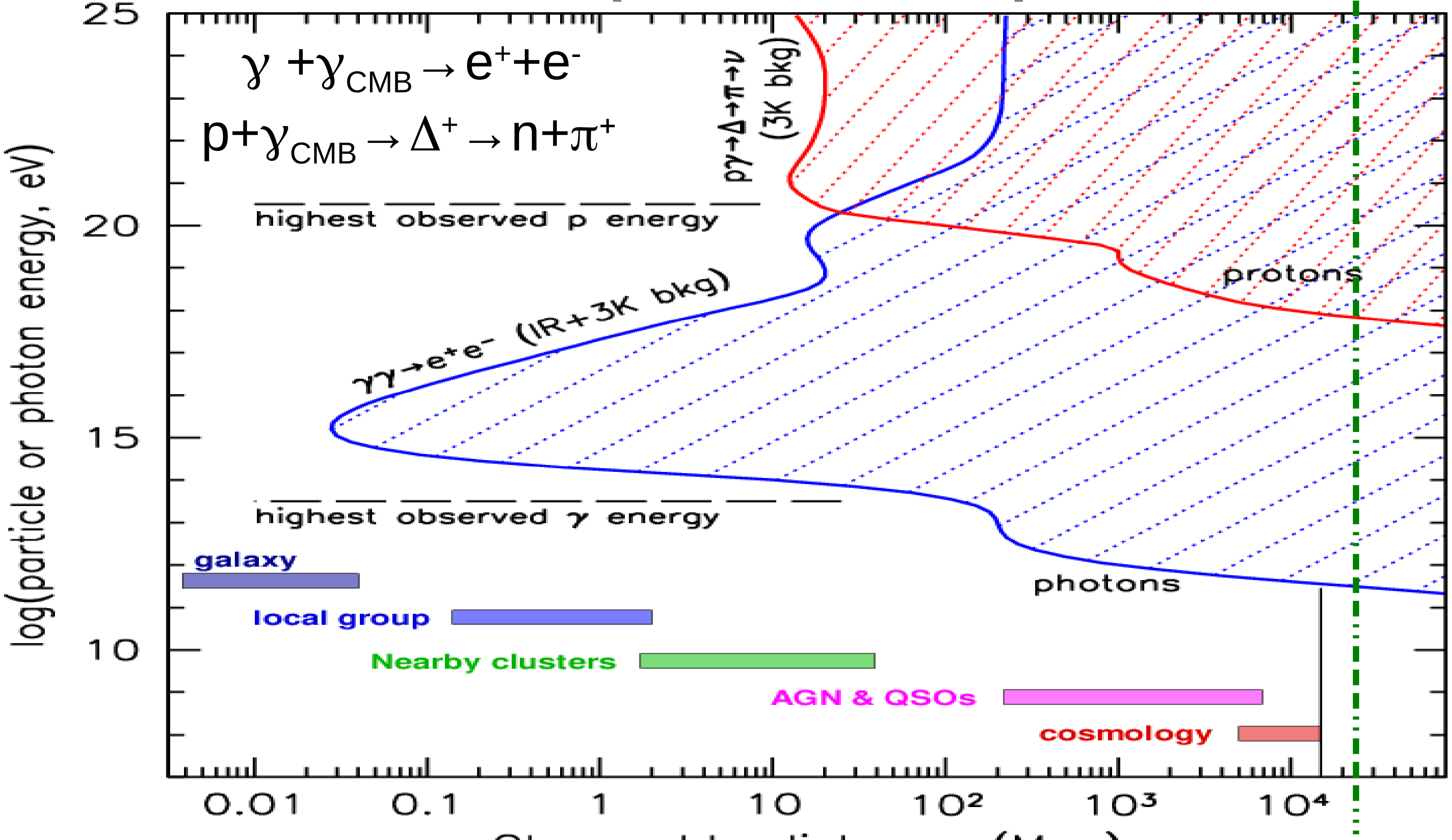


dN/dE (charged) at high energy end!
Telescope Array (Utah, USA) and Auger Experiment (Malargue, Argentina) surface array experimental results

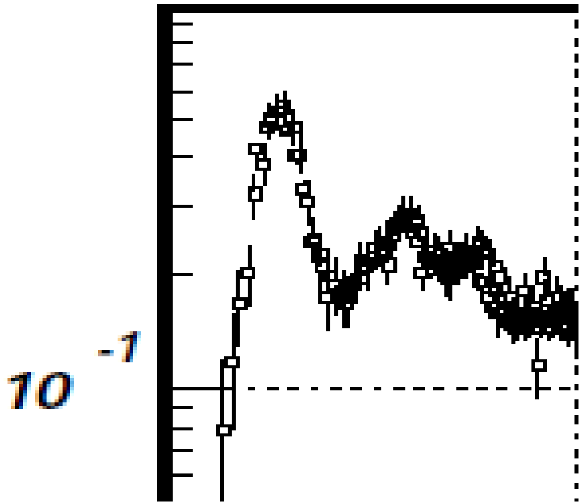




Universe is not transparent for HE photons or nuclei!



Calculate the proton-energy threshold for p+γ_{CMB} → $\Delta^+(1232)$



Cross section for γp scattering in mb;
Prob interaction in dx=Nσdx;
N=400/cm^3
dx~(1/16) x 10^{24} m
1 Mpc=3 x 10^{22} m

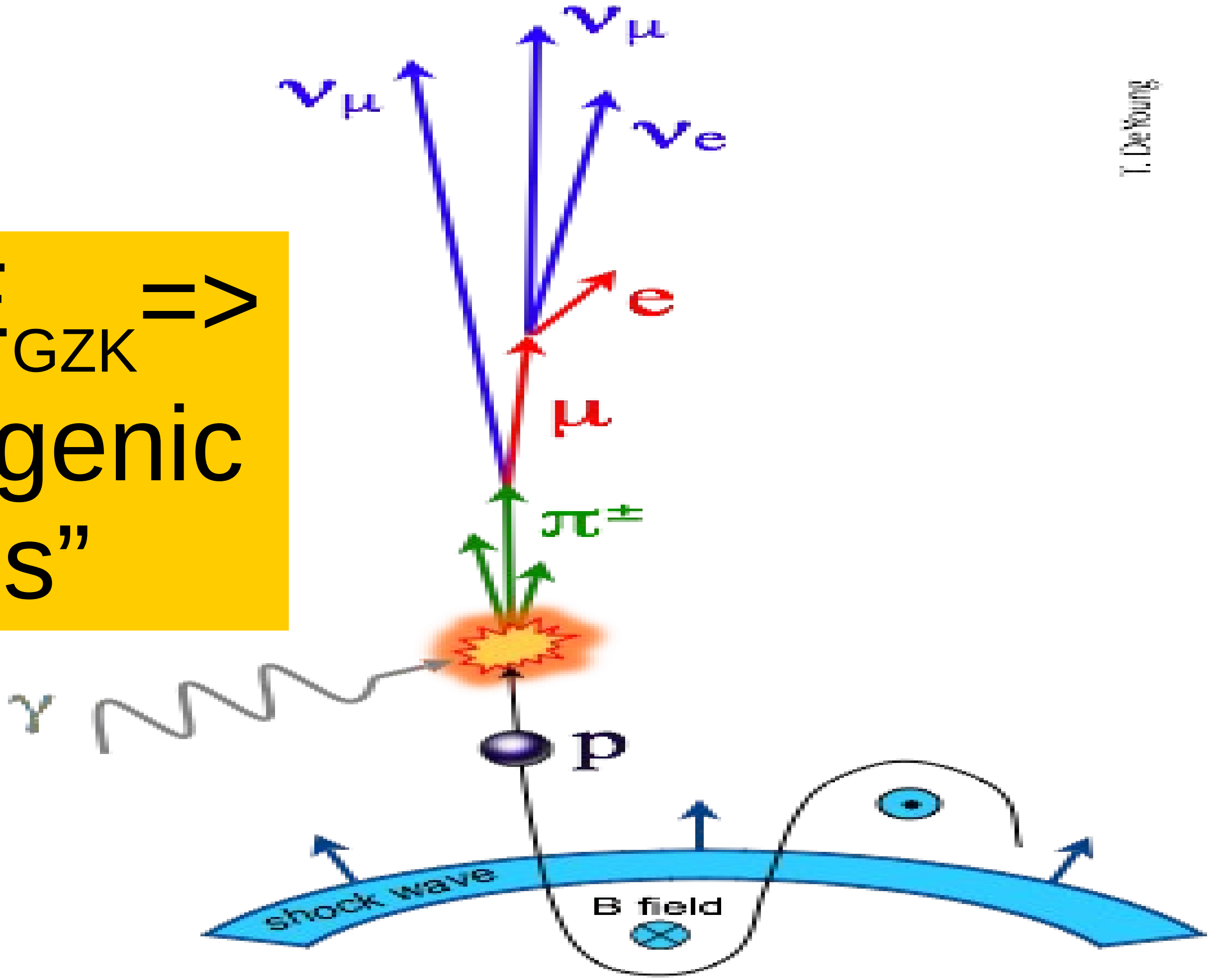
b) Do **free** neutrons feel the GZK effect? (6 Mpc; 1 Mpc=3.085 x 10^{22} m)

If CMB photons are everywhere, how can cellphones work?

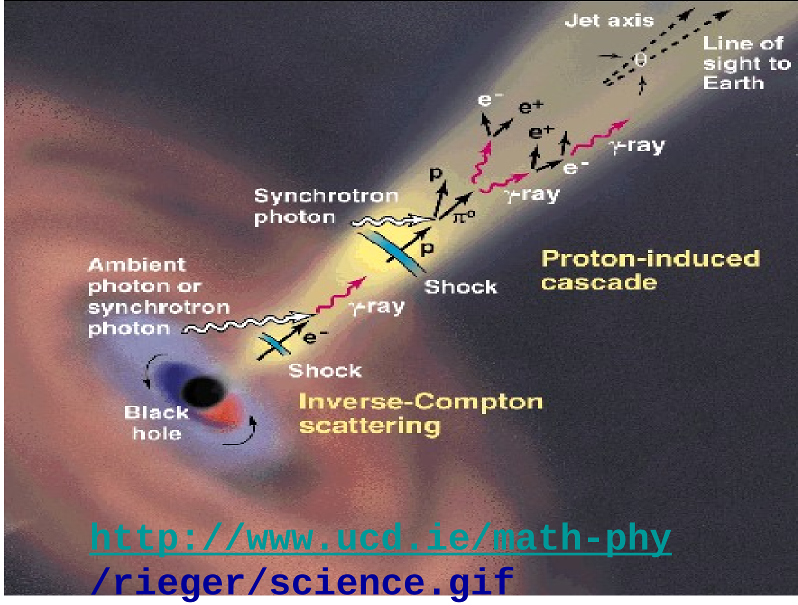
What is the GZK cutoff at z=5?

Proton → Neutrino Production in Pictures

For $E>E_{GZK}$=>
"Cosmogenic neutrinos"



UHE nu from blazars



http://www.ucd.ie/math-phy/rieger/science.gif

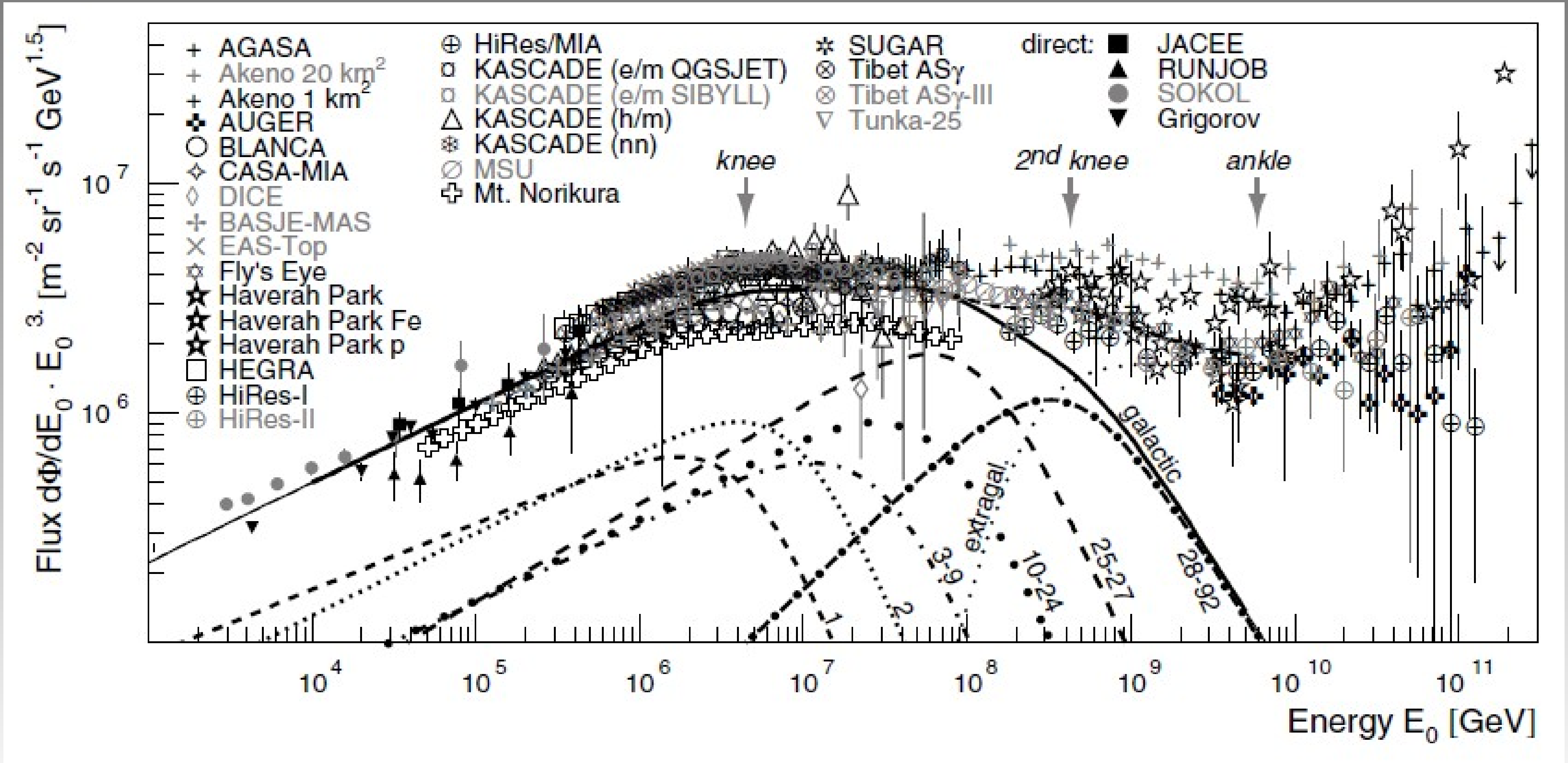
- CR acceleration occurs in jets
  - AGN or GRB
- Abundant target material
  - Most models assume photo-production:
    - $p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + \gamma\gamma$
    - $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu + \nu$
- Ideal case (~ "Waxman-Bahcall limit")
  - Strong magnetic fields retain protons in jets
  - Neutrons escape, decay to protons & become UHECR
  - Extra-galactic cosmic rays observed as protons
  - Energy content in neutrinos ≈ energy in UHECR

Waxman, Bahcall, PRD 59, 023002 (1998). Also TKG astro-ph/9707283v1

Calculate the photon-energy threshold for

$\gamma + \gamma_{CMB} \rightarrow e^+e^-$

Existing explanation of CR spectrum



Jörg R. Hörandel, 2007

$N_p/\mathrm{cm}^3 \times \langle E_p \rangle$

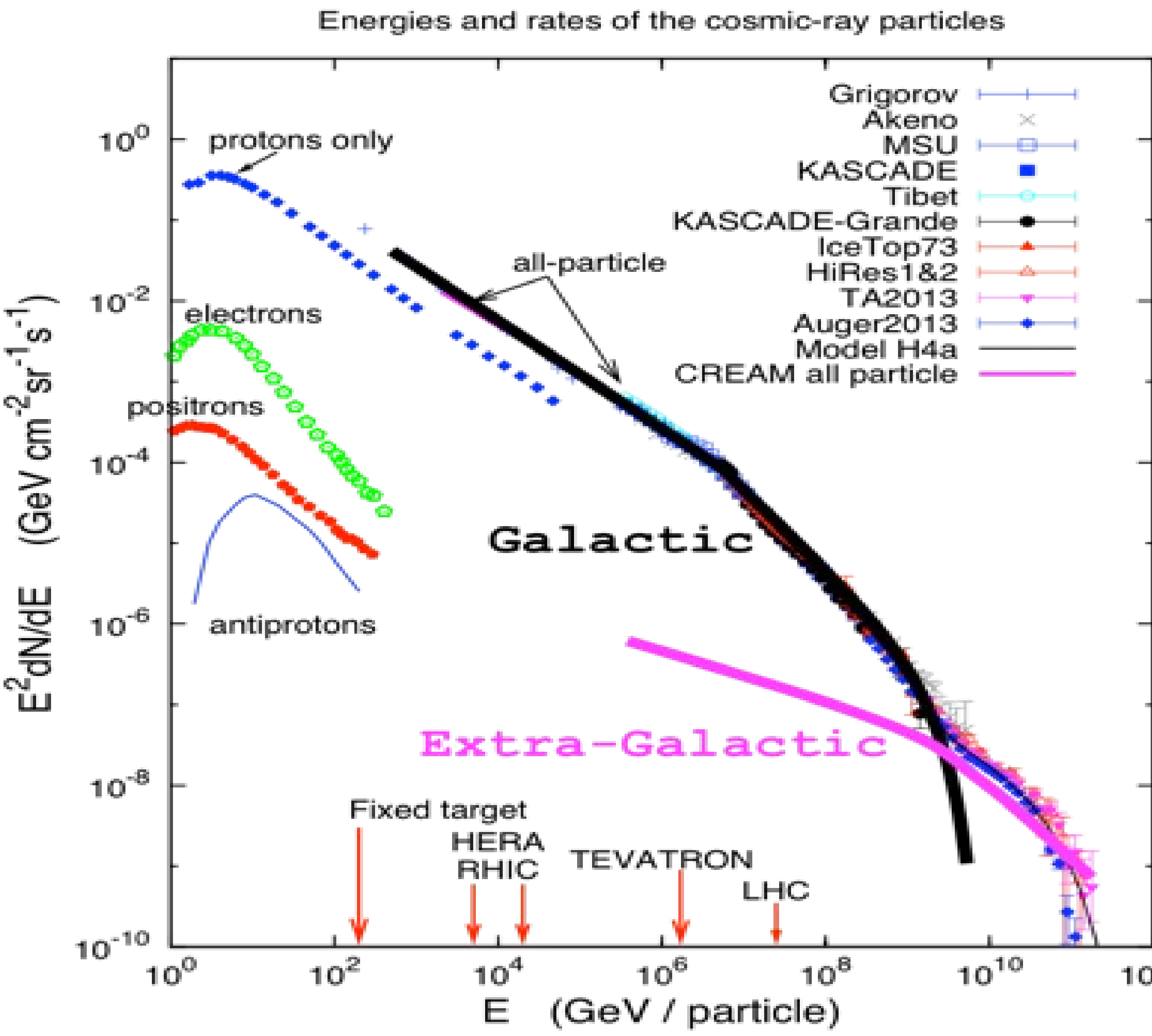
~

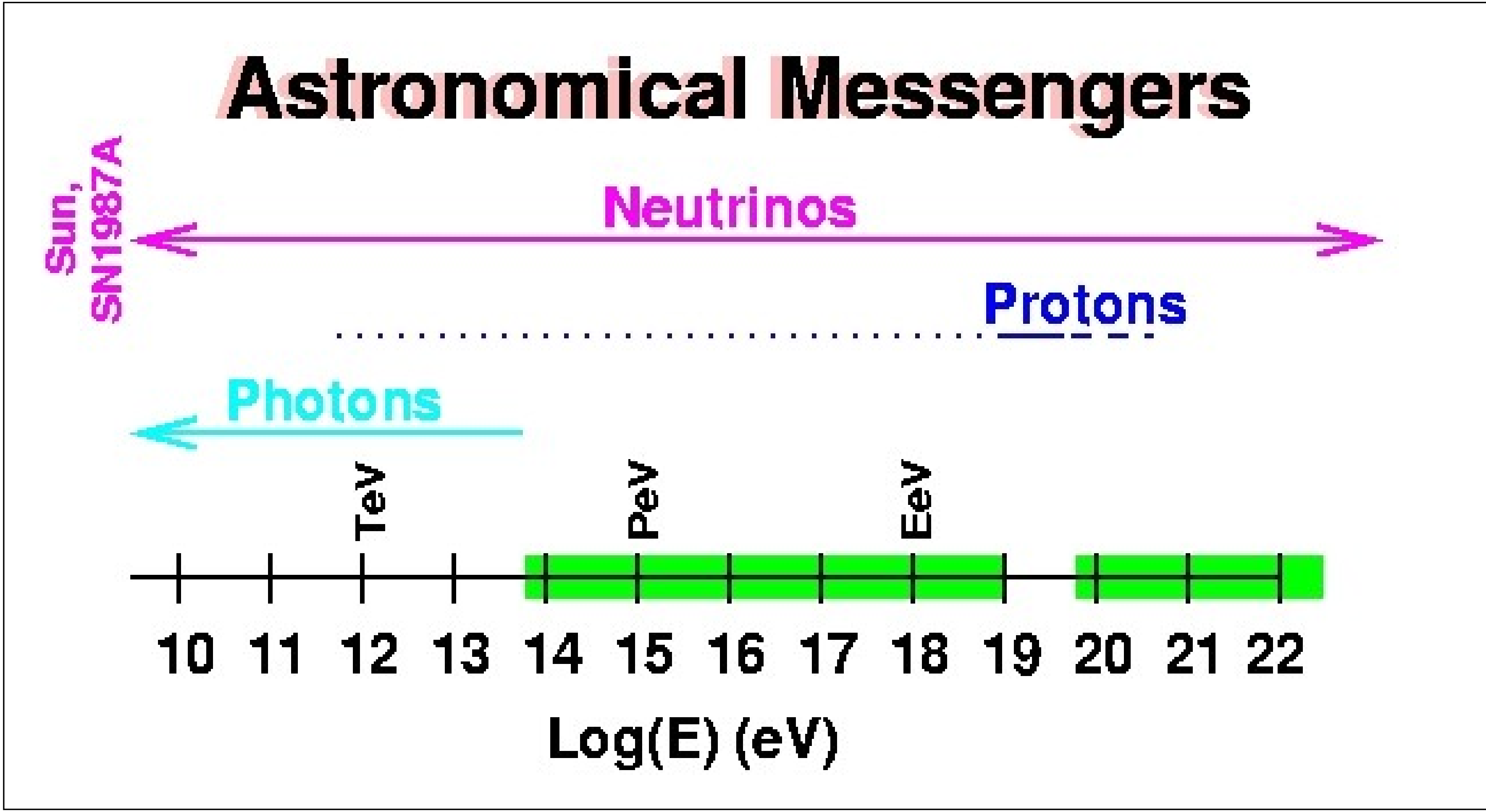
$N_\nu/\mathrm{cm}^3 \times \langle E_\nu \rangle$

~

$N_\gamma/\mathrm{cm}^3 \times \langle E_\gamma \rangle$

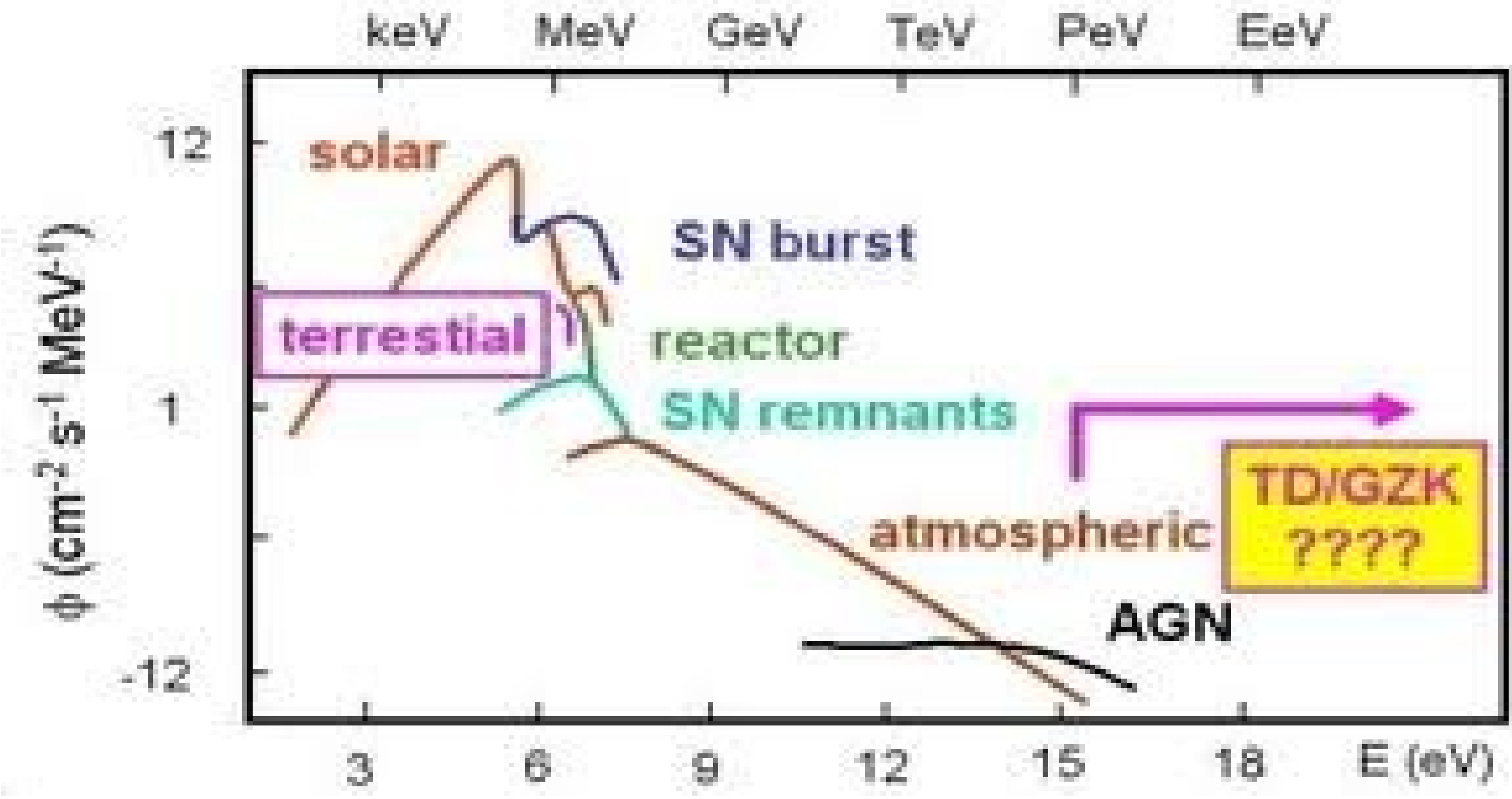
=>common production mechanism!





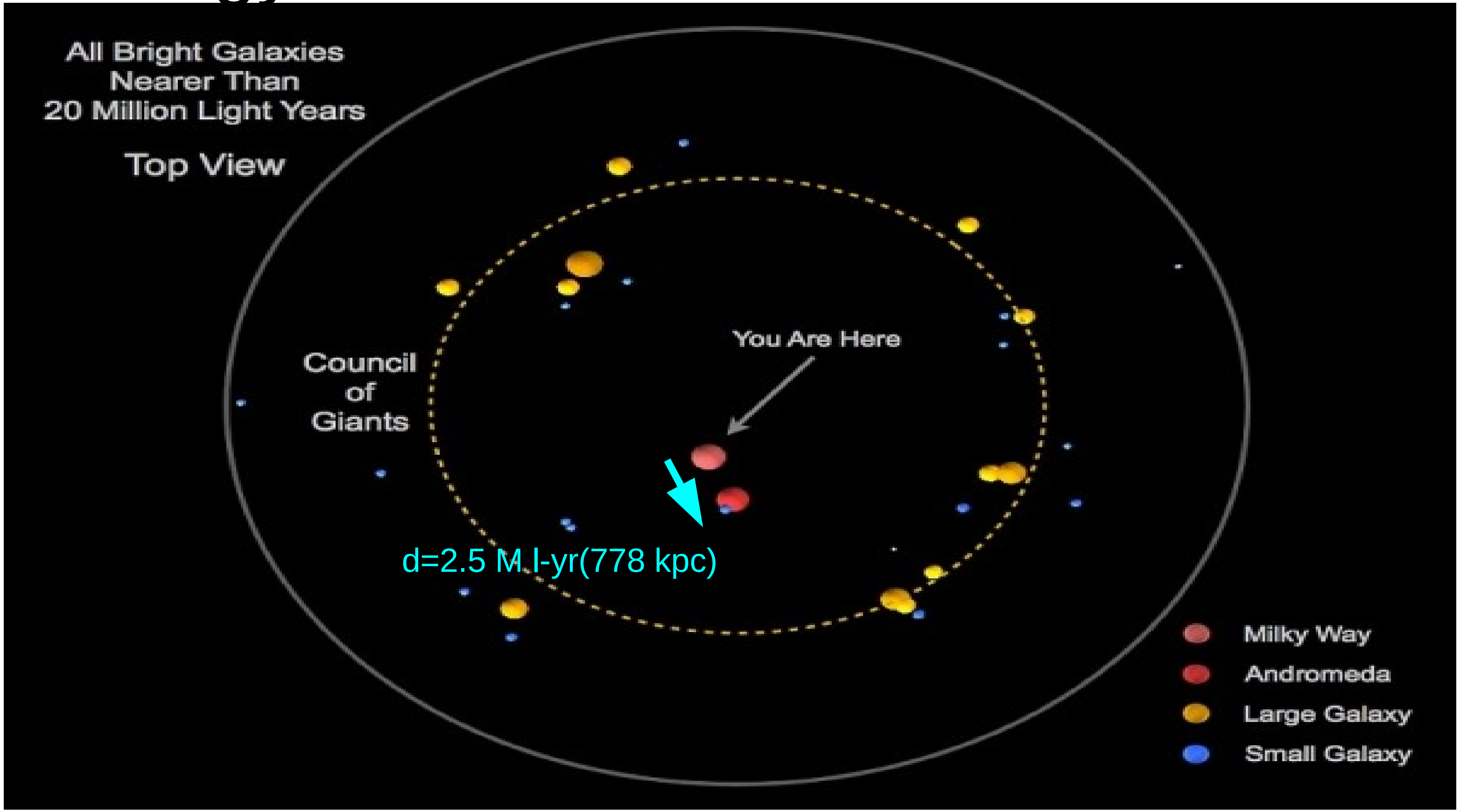
Astronomical Messengers
Sun,
SN1987A
Neutrinos
Protons
Photons
TeV
PeV
EeV
10
11
12
13
14
15
16
17
18
19
20
21
22
Log(E) (eV)

What does the expected Neutrino flux look like?



Neutrons?

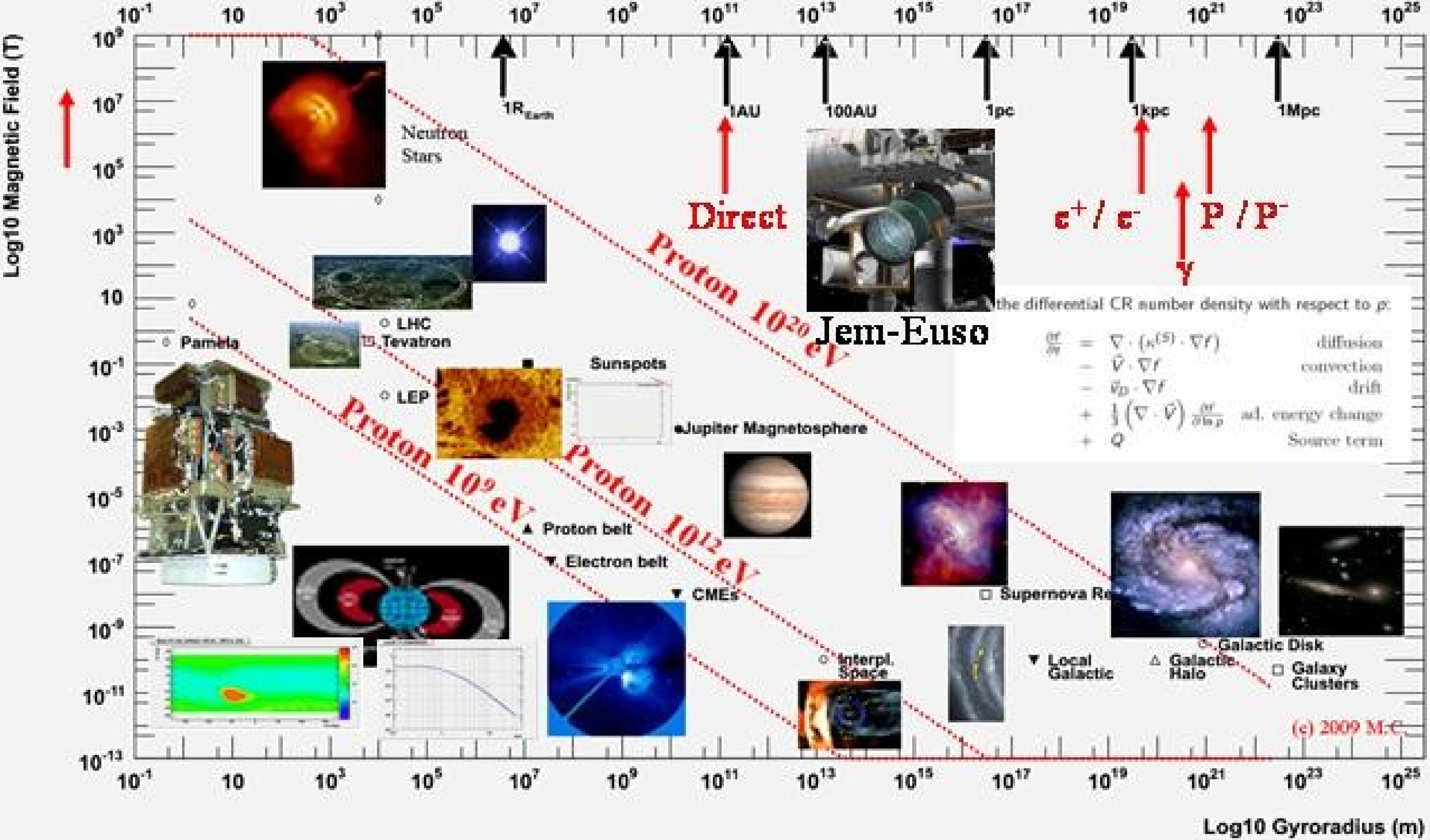
- A free neutron has τ=881 s. Determine the minimum Enrgy for a neutron to reach Earth from Andromeda.



How do you get high-energy CR’s?

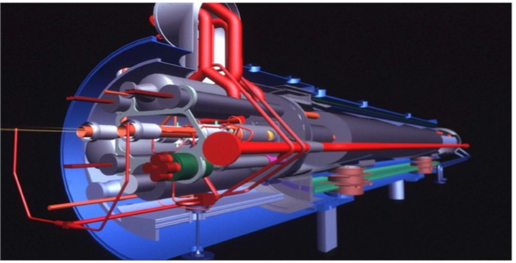
- Need to confine, e.g., a charged particle in a magnetic field ‘accelerator’ for enough revolutions so that it can obtain a high-energy

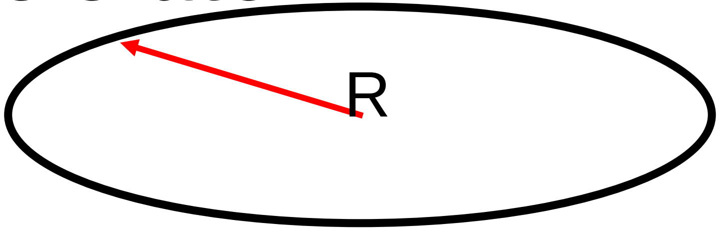
=>Need large product of B-field x gyroradius



Log10 Magnetic Field (T)
Log10 Gyroradius (m)
1R_Earth
1AU
100AU
1pc
1kpc
1Mpc
Neutron Stars
Direct
Jem-Euso
e+ / e-
γ
P / P-
Proton 10^20 eV
Proton 10^12 eV
Proton 10^9 eV
LHC
Tevatron
Pamela
LEP
Sunspots
Jupiter Magnetosphere
Proton belt
Electron belt
CMEs
Interpl. Space
Supernova Re
Local Galactic
Galactic Halo
Galactic Disk
Galaxy Clusters
the differential CR number density with respect to p:
diffusion
convection
drift
ad. energy change
Source term
(c) 2009 M.C.

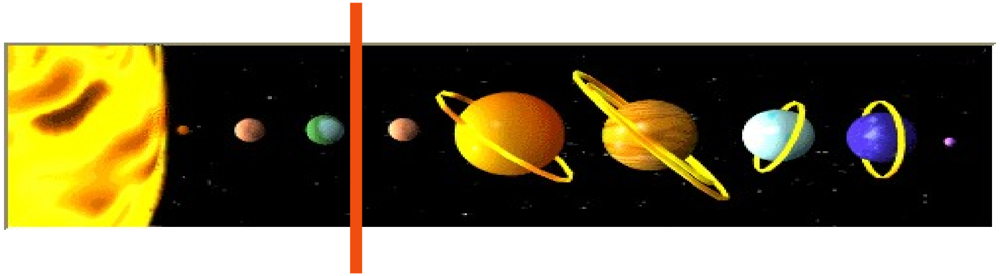
The size of the Universe “LHC” accelerator?



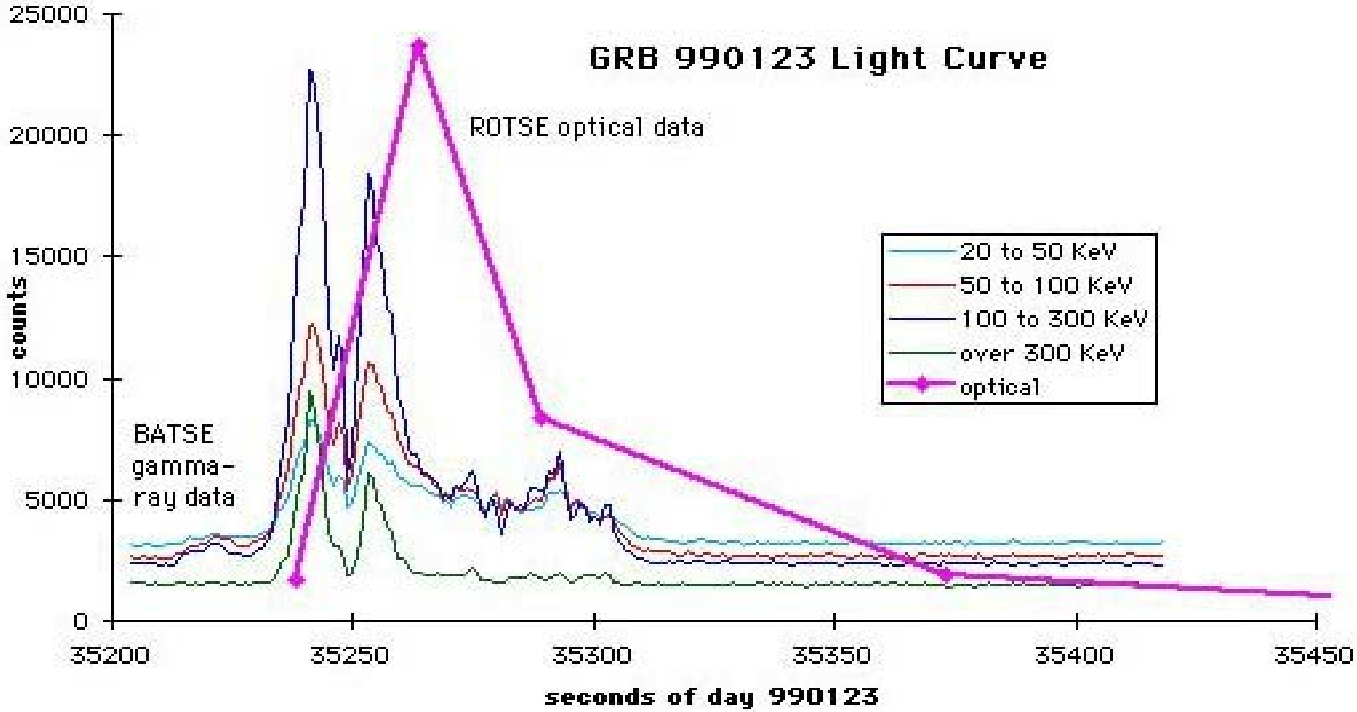


To use LHC magnets to deliver 10^{20} eV we need a radius of the accelerator to be about 1.5 times the distance Earth -Sun (Why?)

$$P_{synchrotron} \sim 2q^2\gamma^4 a^2/3c^3;\ a \sim 1/r$$

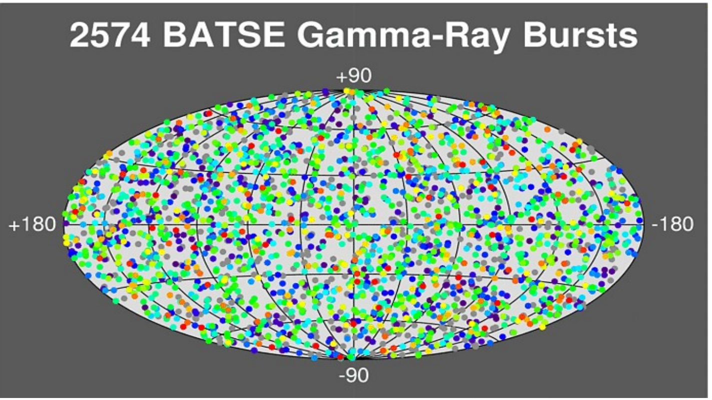


Gamma Ray Bursts (~100 s light curves)

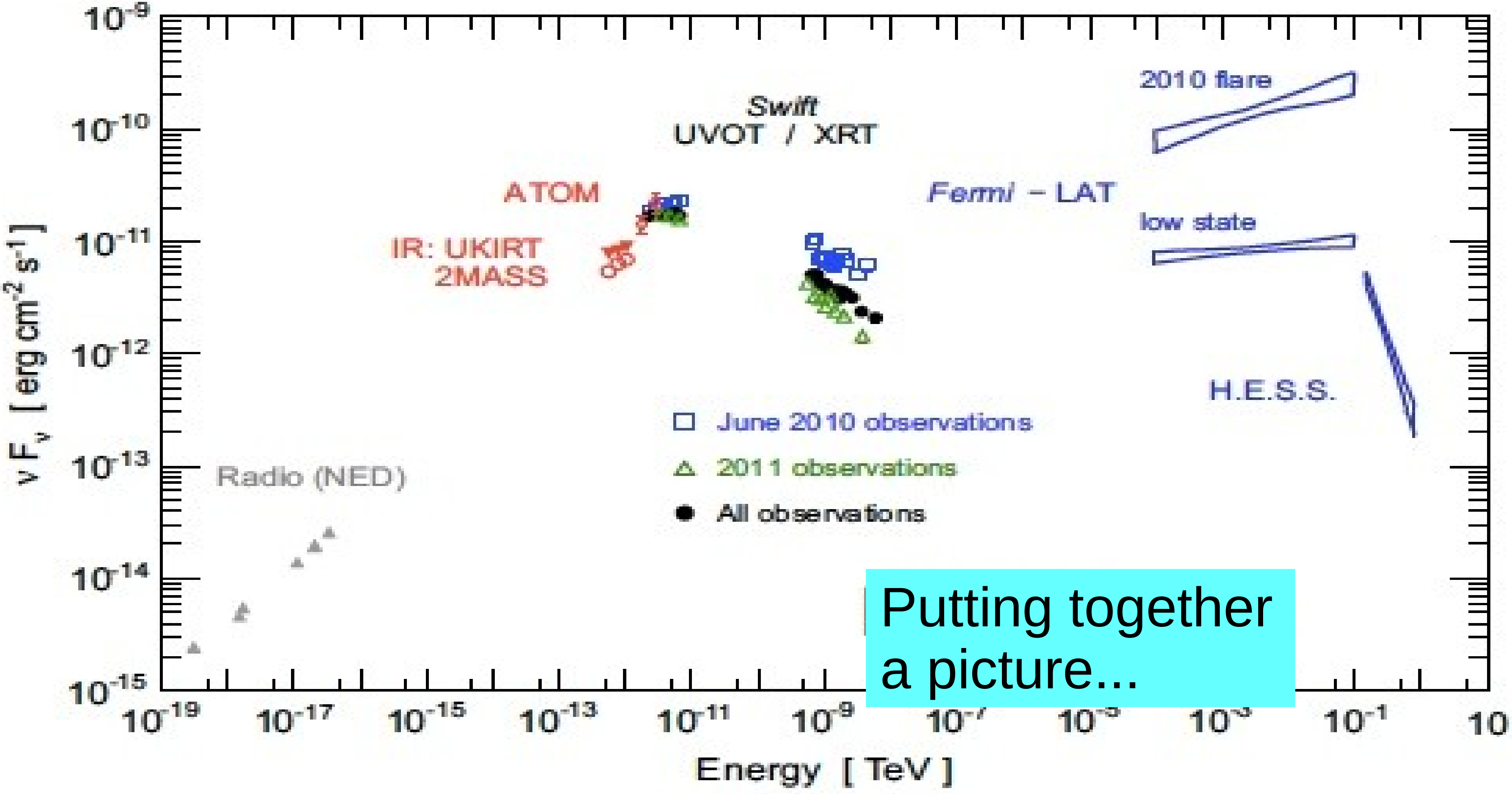


Cosmological sources!

But what are they?

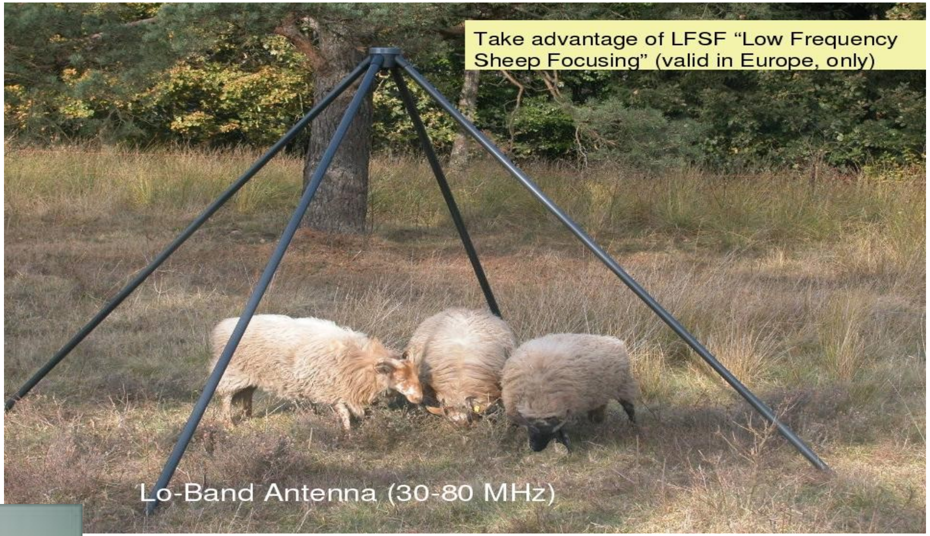


1/10^6 yrs Milky Way (mass extinctions)?



Putting together a picture...

What do experiments look like?



-CR’s are either protons (nuclei), γ, ν - protons interact with solid matter over a distance of cm (targeted cancer therapies, e.g.)

-photons similarly interact over cm (and even sub-cm) length scales (the paper to light trick)

a solar neutrino passes through ~1 light-year of lead before interacting.

Punchline: protons/nuclei/γ interact in the atmosphere and produce `**secondaries**’ at the ground; neutrinos (generally) don’t

Primaries detected in-space

How do we reconstruct the primary from the secondaries?

1) Measure the ionization/scintillation produced when one of the charged particles (e/μ) passes through your ground detector

Includes fluorescence of nitrogen left in wake of shower

2) Measure Cherenkov light produced as (e/μ) traverse the atmosphere, or when (e/μ) pass through, e.g., ground water tank

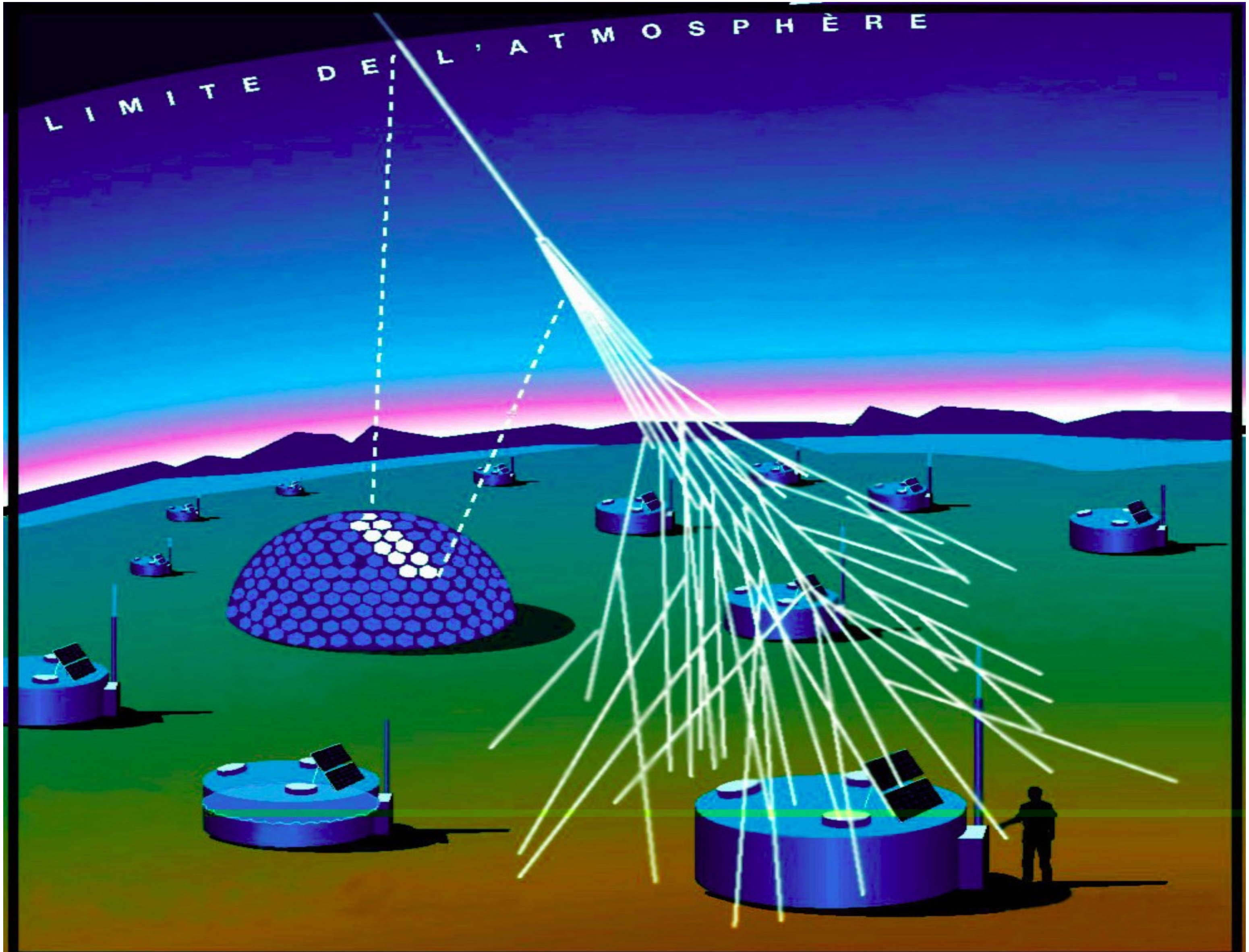
3) Measure the radio-frequency radiation (`geosynchrotron', e.g.) produced as charged particles in shower accelerate and bend in geomagnetic field

Pretty much all surface detector arrays are based on 1)-3)

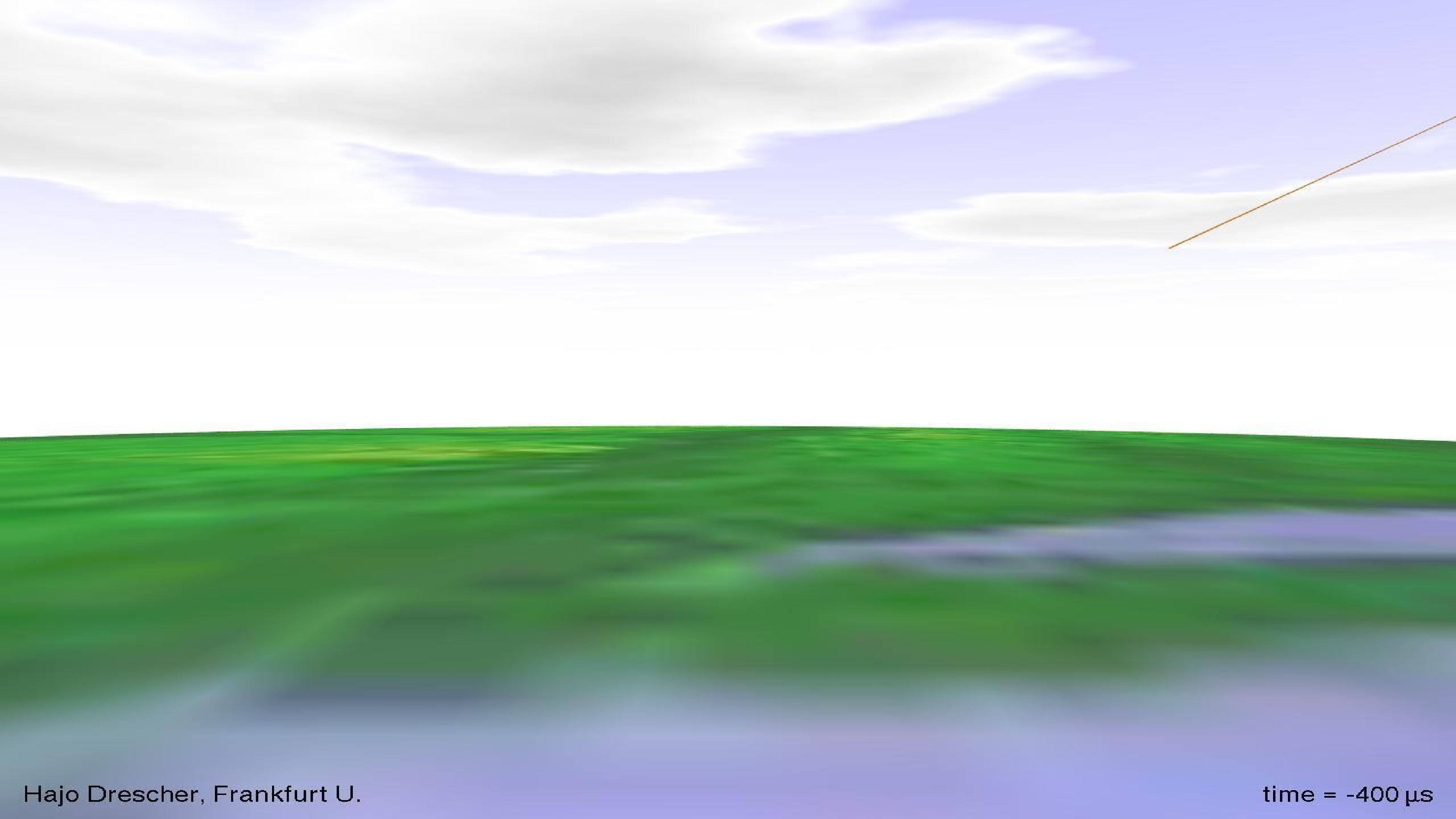
N.B. Since footprint is so large, need to sample=>need model to figure out how much you lost!

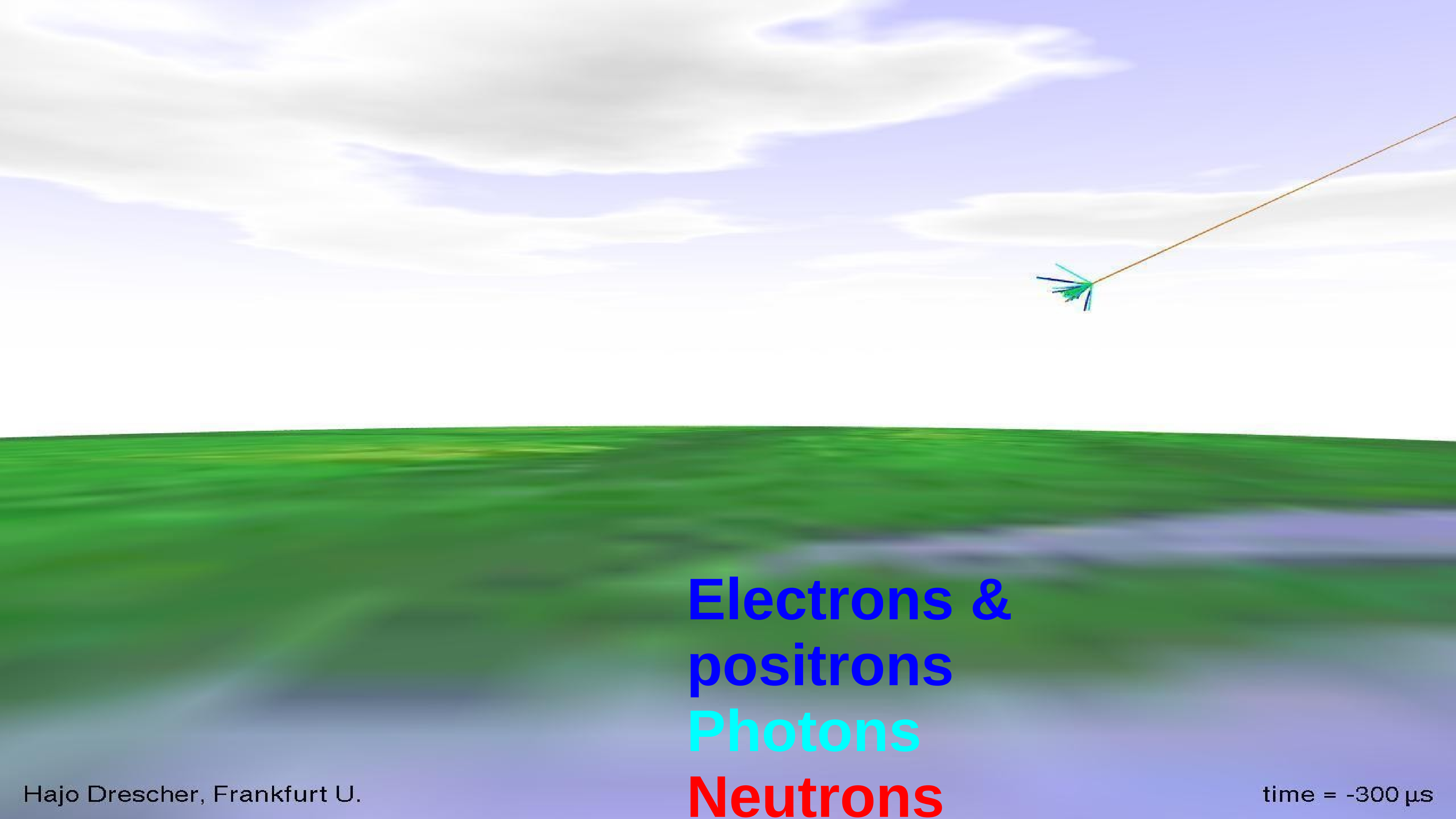
4) Radar techniques? (will discuss, time permitting)

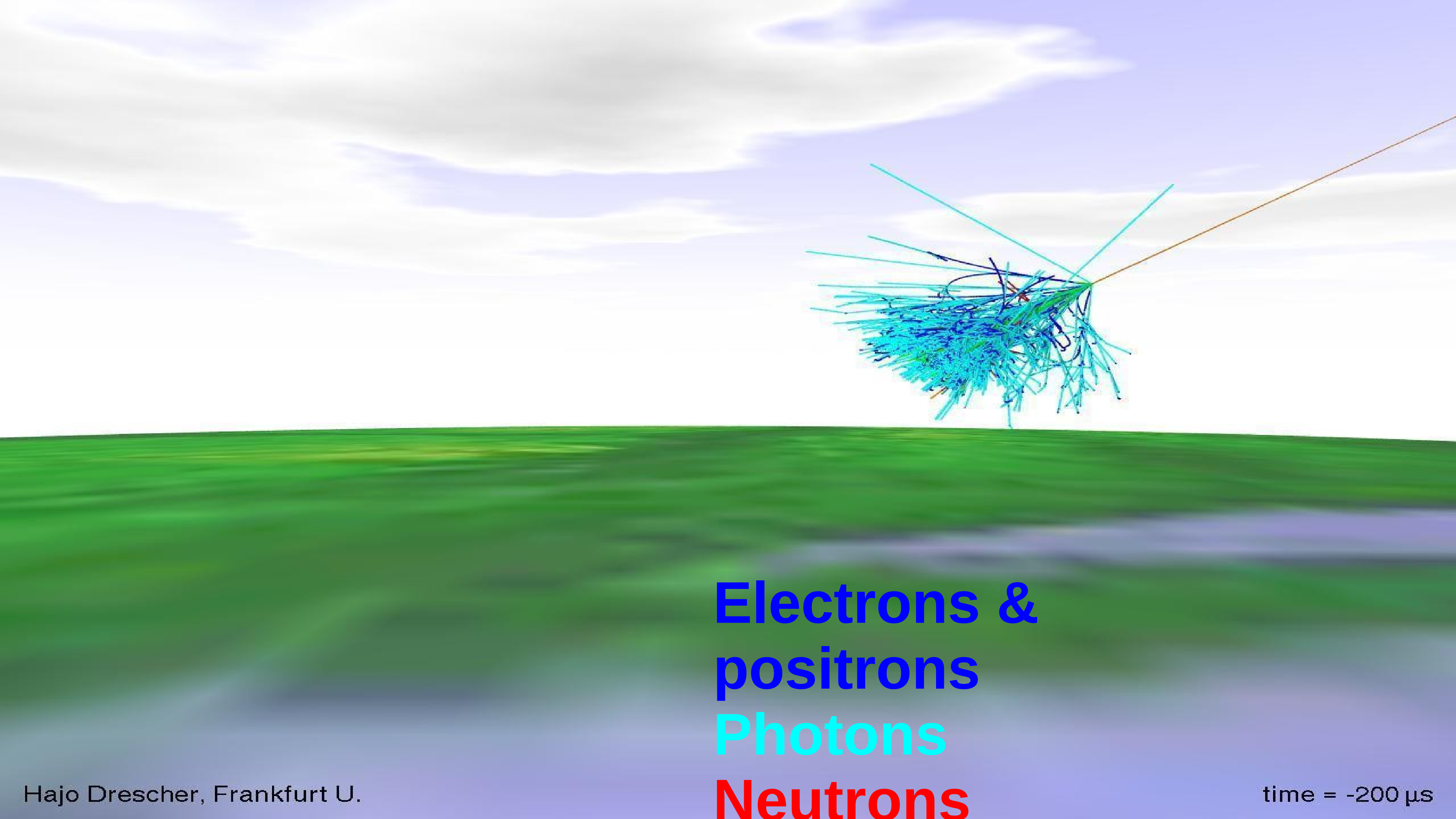
Current Expts & Technique

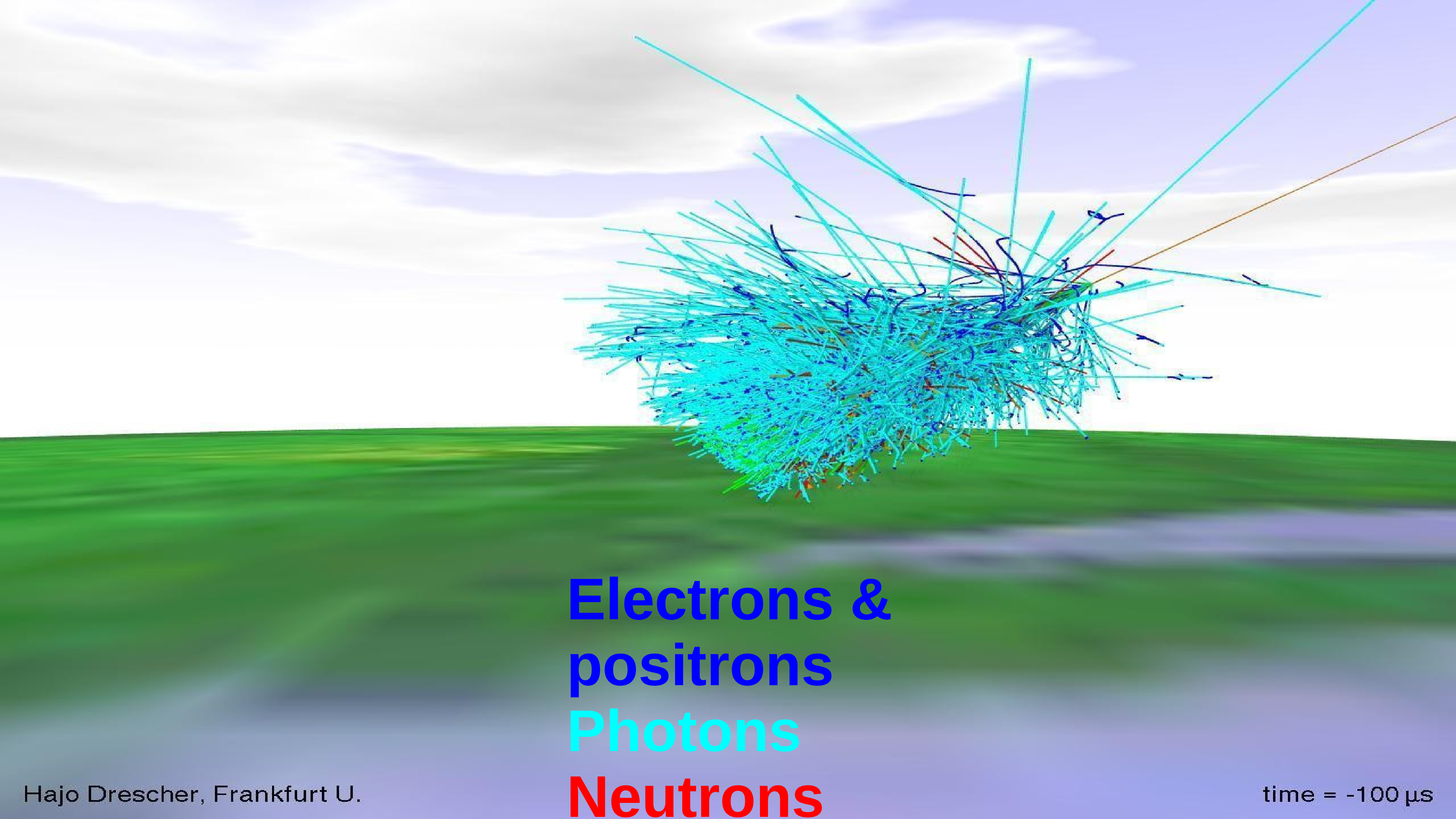


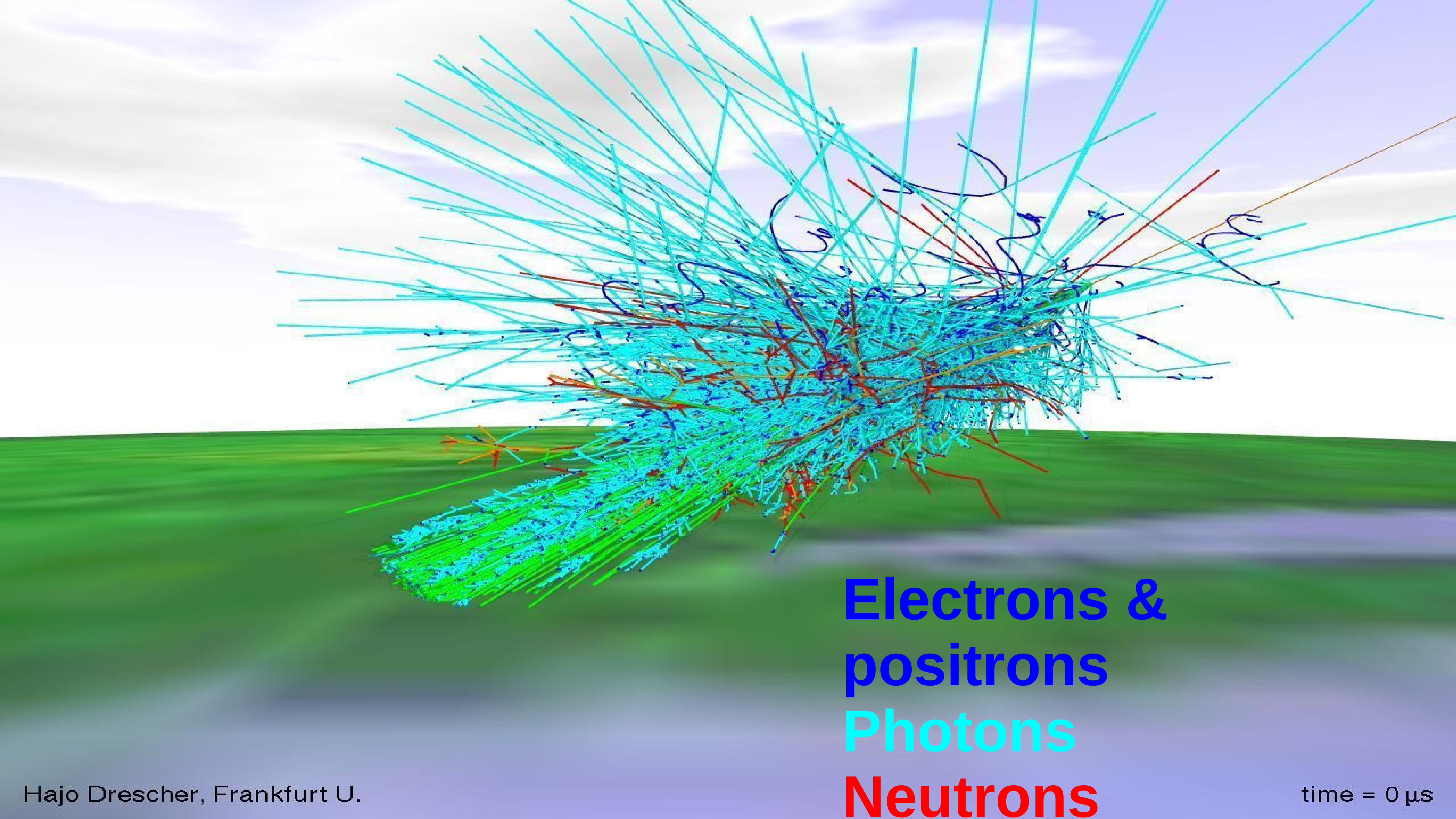
UHE proton detection: 1 J proton interacting in the upper atmosphere?

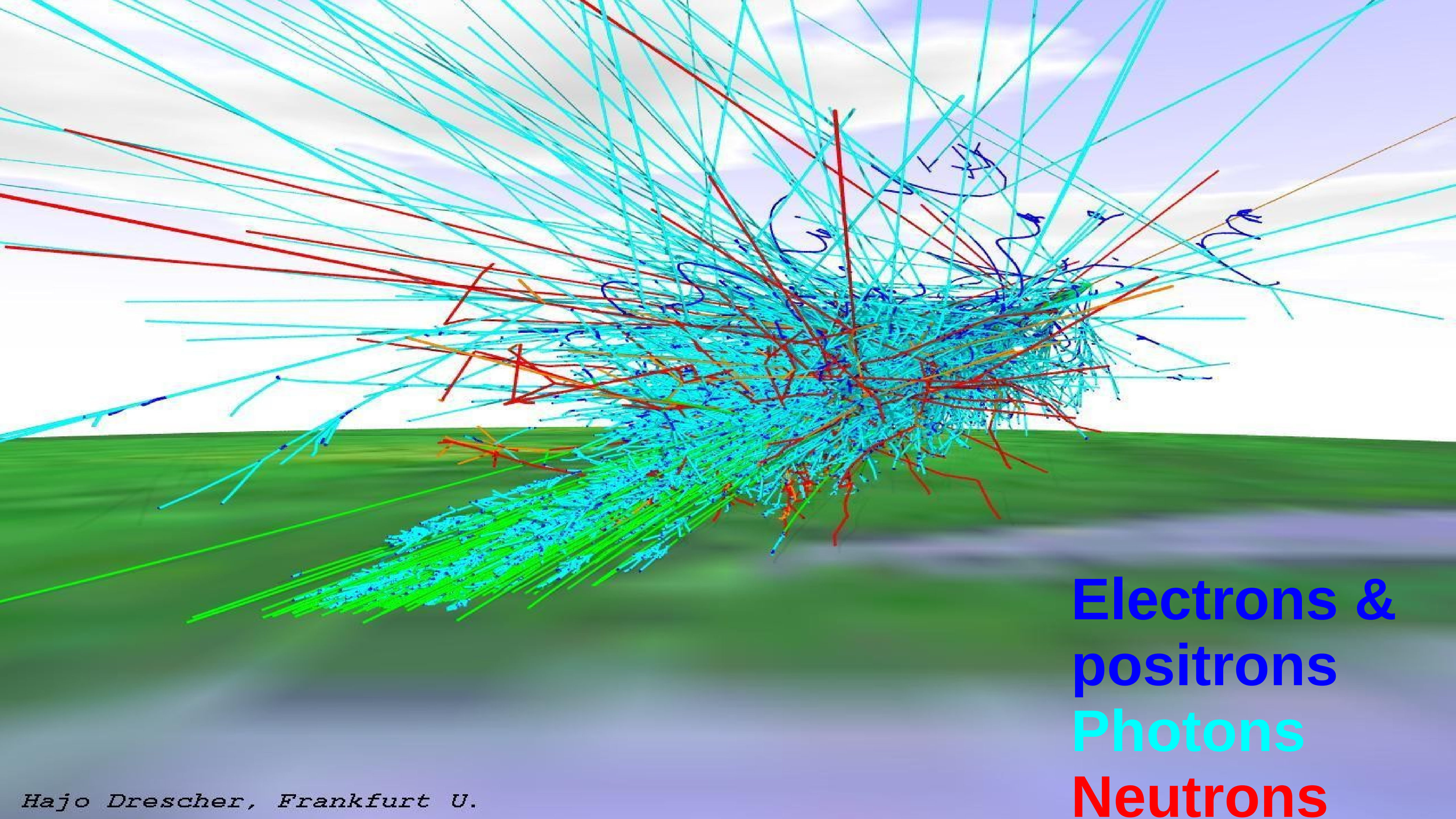

Hajo Drescher, Frankfurt U.
time = -400 µs

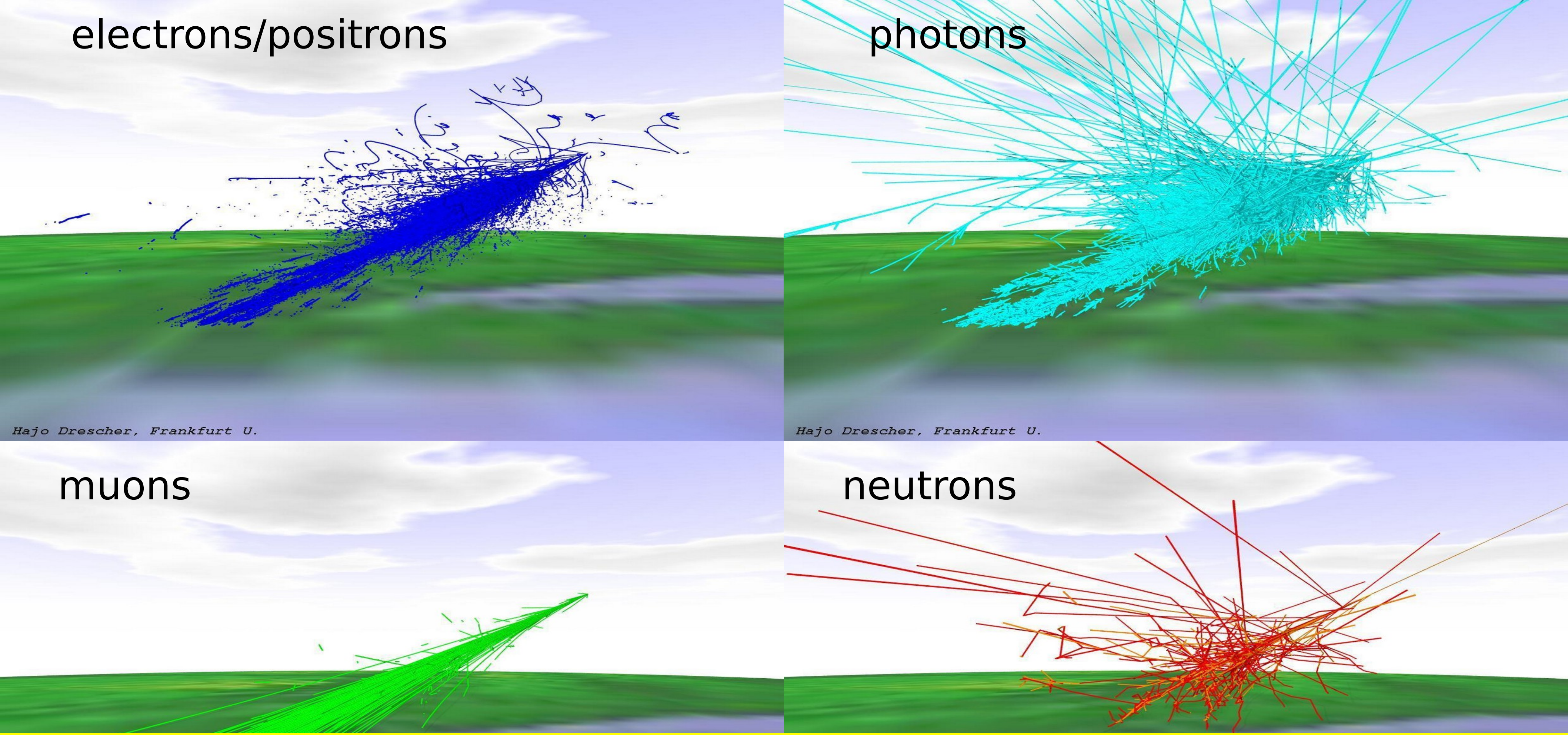

Electrons &
positrons
Photons
Neutrons
Hajo Drescher, Frankfurt U.
time = -300 µs


Electrons &
positrons
Photons
Neutrons
Hajo Drescher, Frankfurt U.
time = -200 µs


Electrons &
positrons
Photons
Neutrons
Hajo Drescher, Frankfurt U.
time = -100 μs

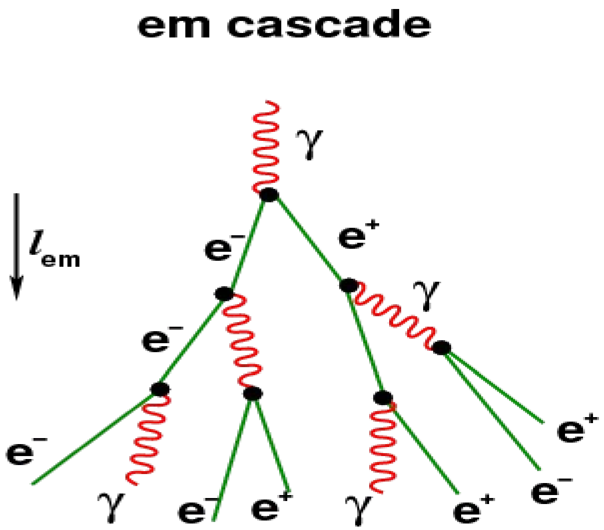

Electrons & positrons
Photons
Neutrons
Hajo Drescher, Frankfurt U.
time = 0 μs

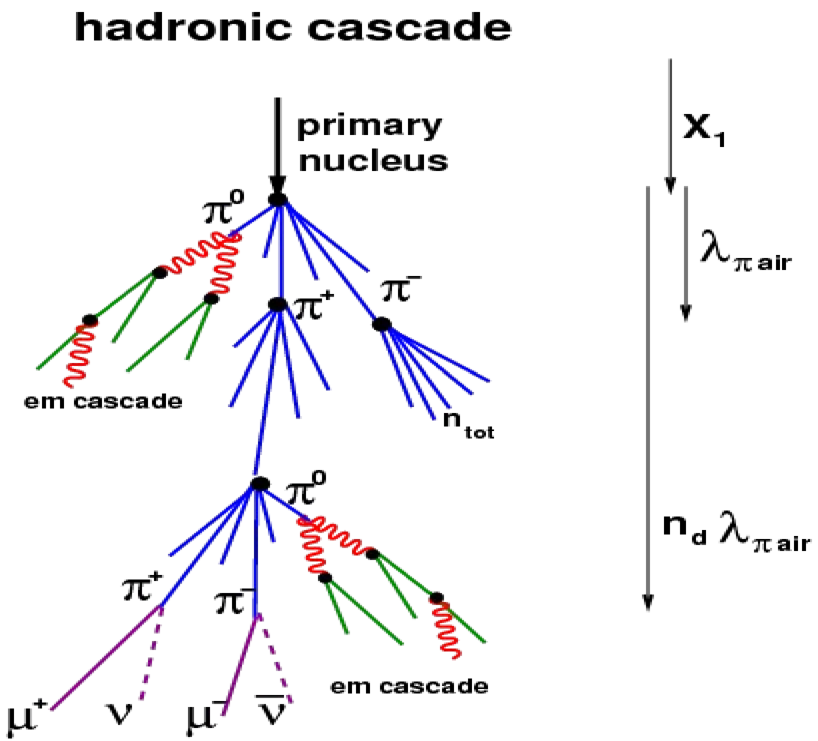

Electrons &
positrons
Photons
Neutrons
Hajo Drescher, Frankfurt U.



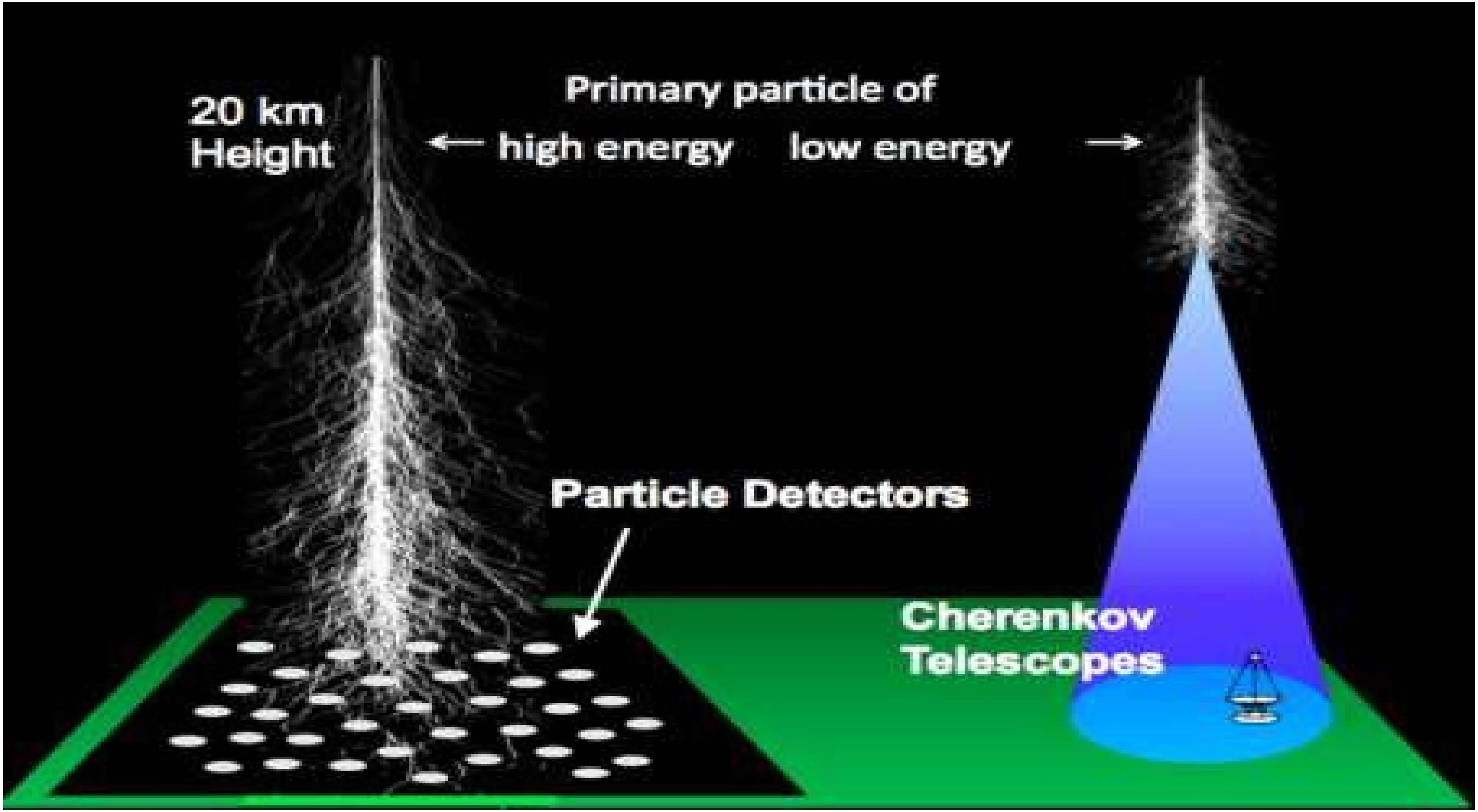
1) Assuming Heitler model (e), estimate the number of positrons, electrons and photons at a depth of $4X_0$ (assume the atmosphere has uniform density) 2) Estimate optimal detector height for detecting a 1 Joule electron, assuming we want to place the detector at shower maximum and using the data on the graphs on the next page, 3) How does t grow with $E_{primary}$: a) linearly, b) quadratically, c) logarithmically?

EM-only vs. hadronic showers

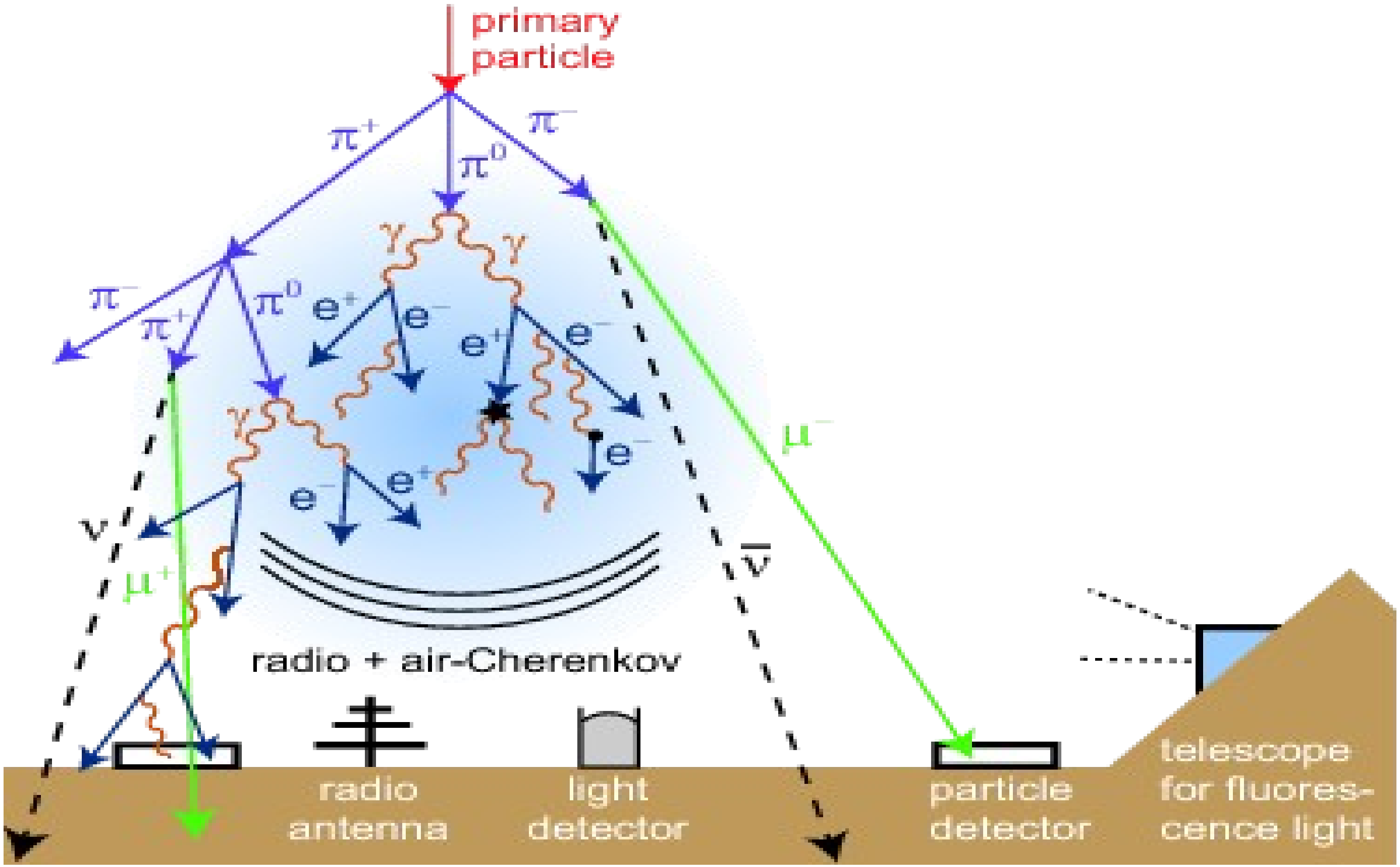




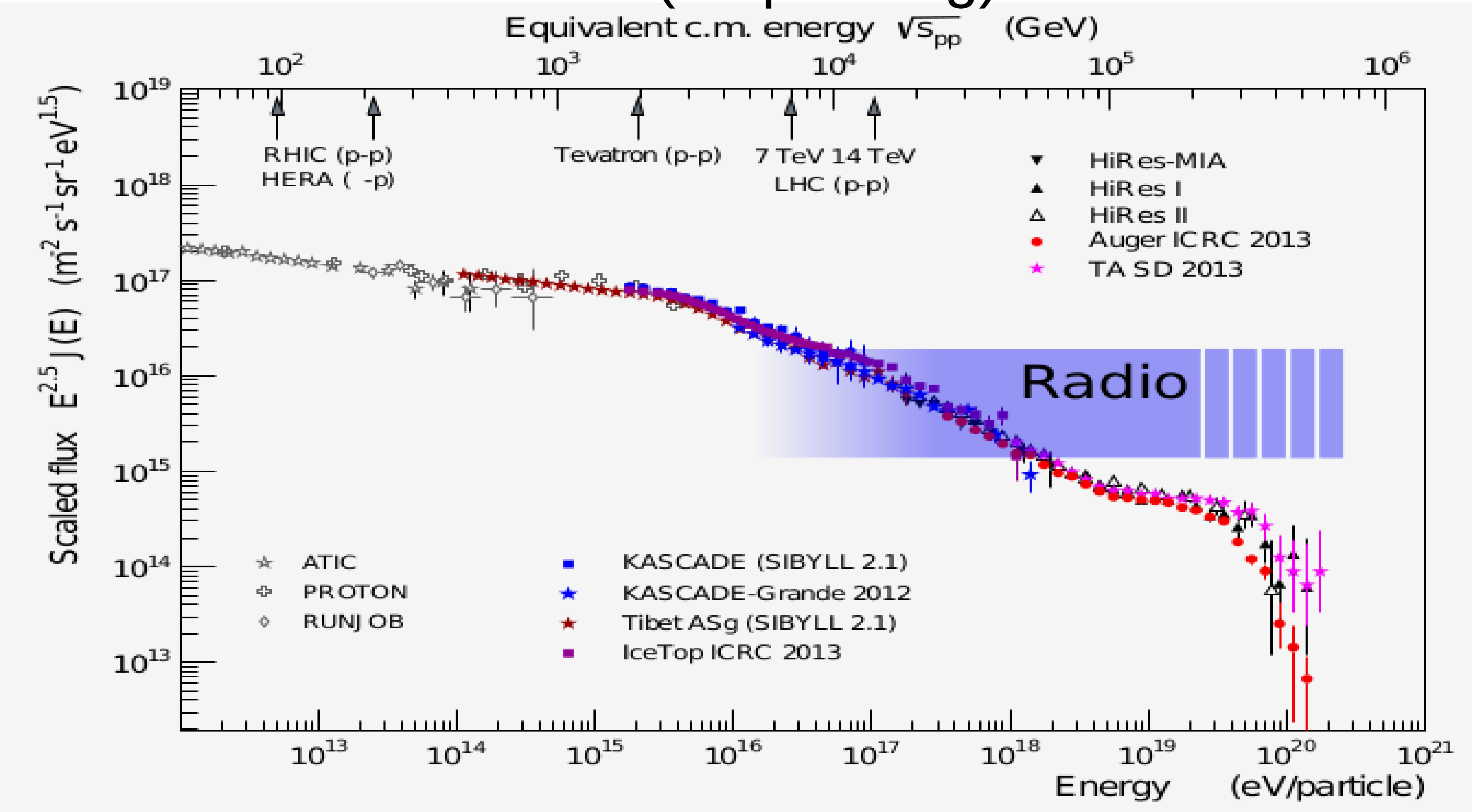
gamma-detection, e.g.



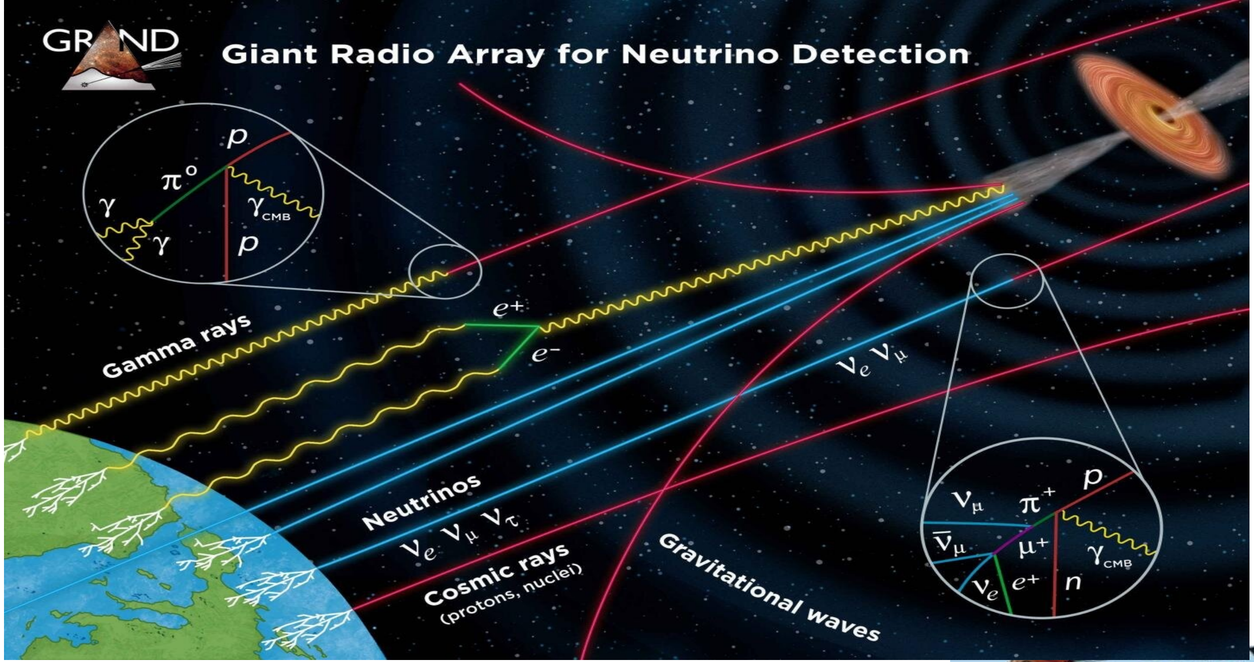
Surface Detector arrays now include radio!



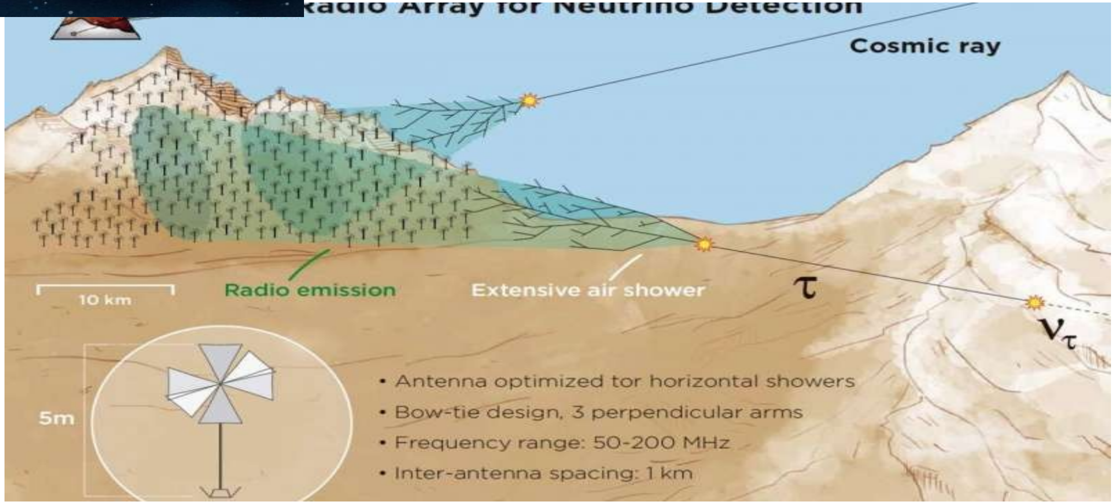
Radio (no phasing)



Q: The nominal energy threshold of in-air radio detection is 100 PeV. Assuming an $E^{-2.7}$ charged spectrum, how many more events (roughly) do you detect by phasing (perfectly) 16 antennas?



In-air UHECR detection using radio techniques



20 separate, independent sub-arrays, each of 10 000 radio antennas deployed over 10 000 km^2

New technique of Local Muon Density Spectra

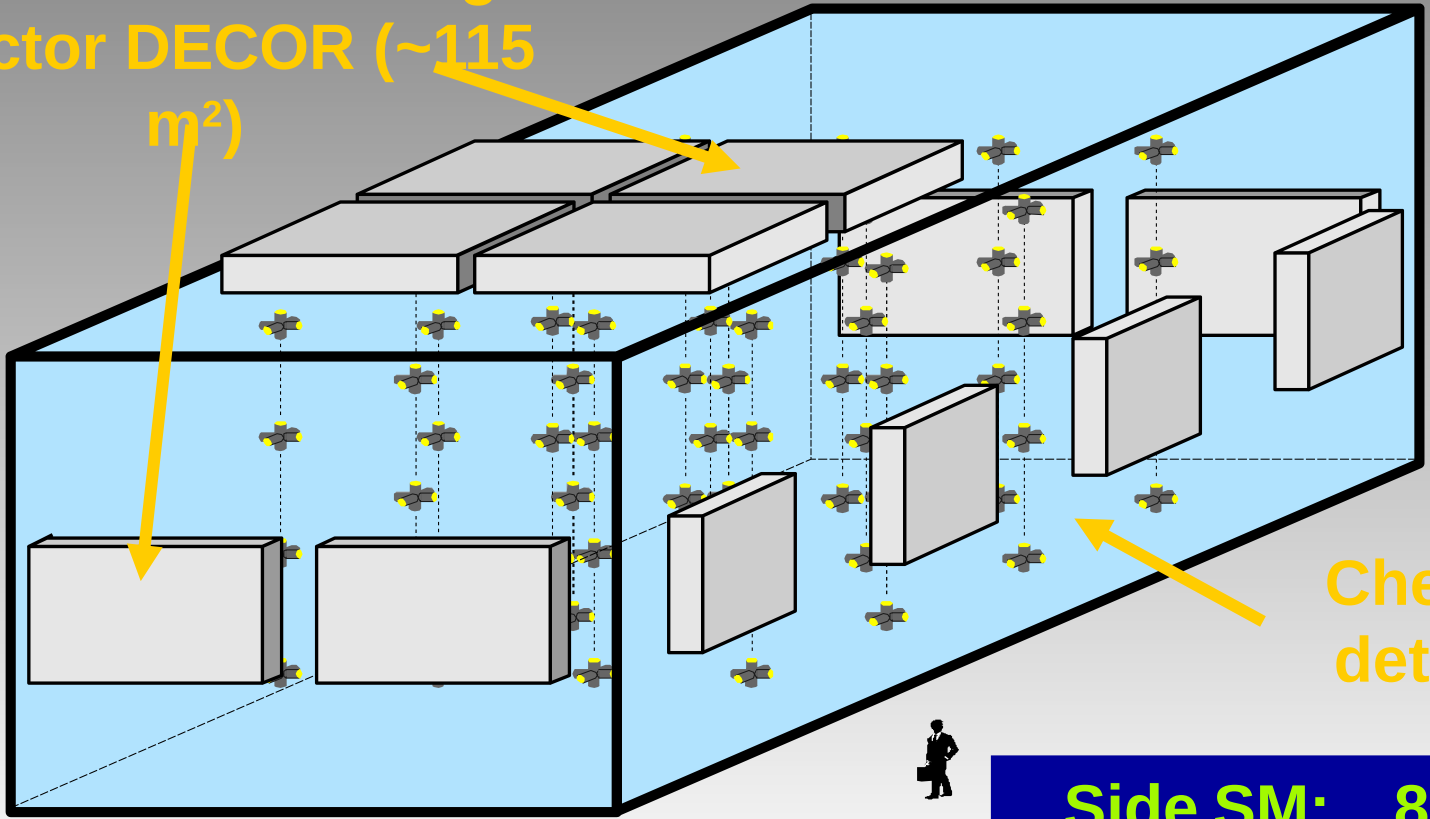
was realized by means of

Experimental complex NEVOD-DECOR

Russian-Italian Collaboration

National Research Nuclear University MEPhI, Russia
Istituto di Fisica dello Spazio Interplanetario, INAF, Torino, Italy
Dipartimento di Fisica Generale dell' Universita di Torino , Italy

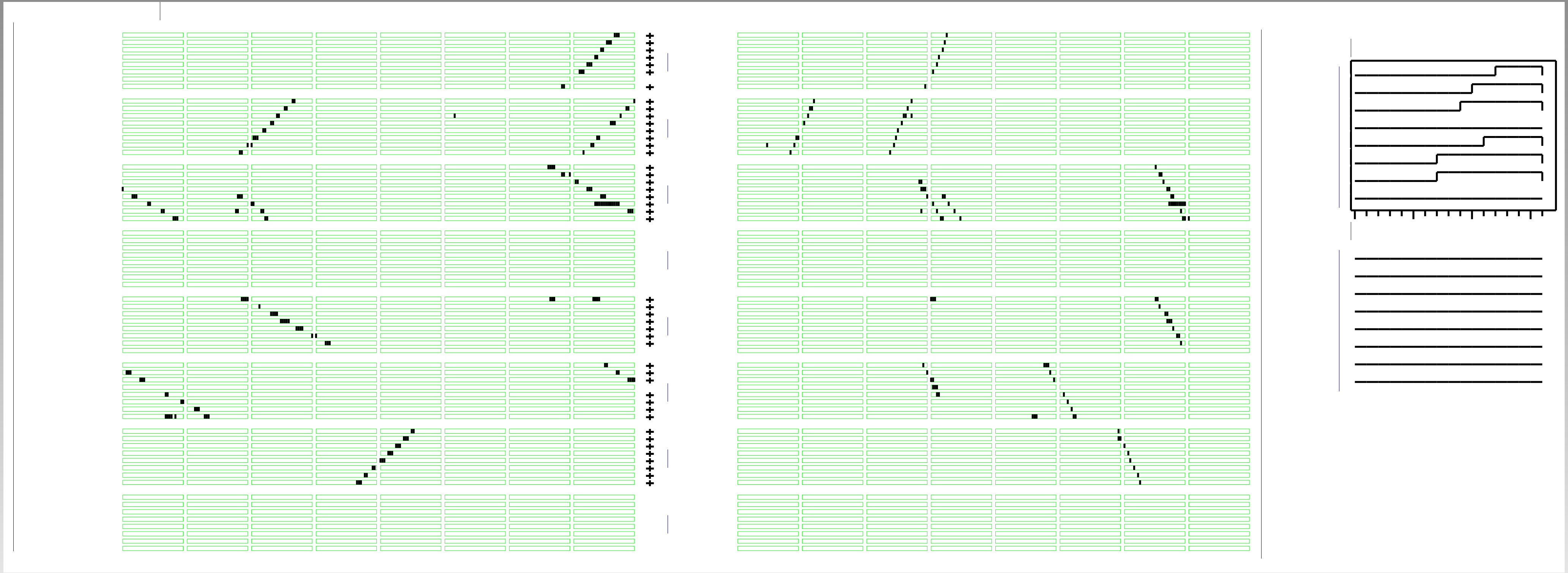
General view of NEVOD-DECOR complex



Side SM: 8.4 m^2 each

- $\sigma_x \sim 1$ cm; $\sigma_\psi \sim 1°$

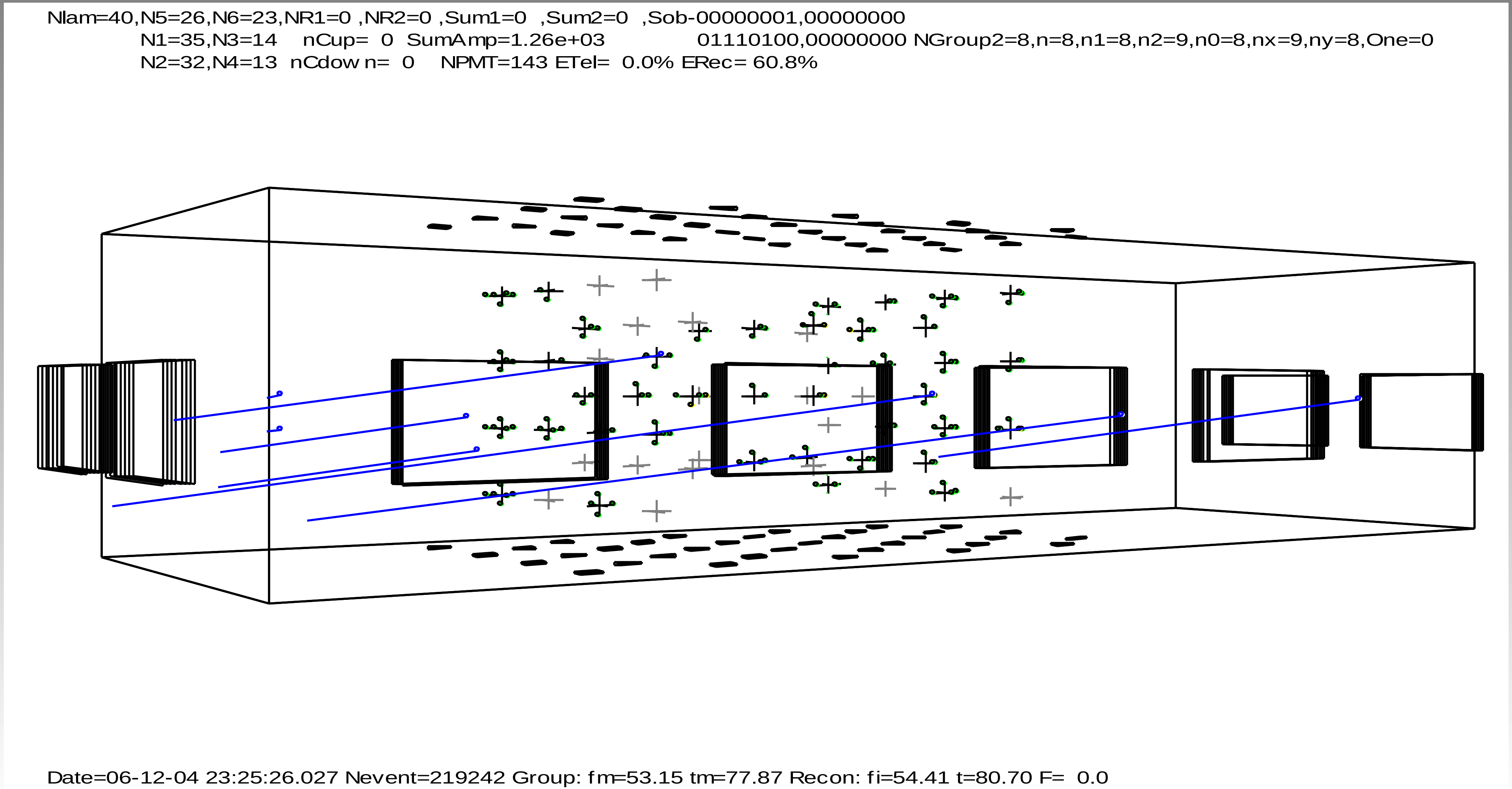
A typical muon bundle event in Side DECOR
(9 muons, 78 degrees)



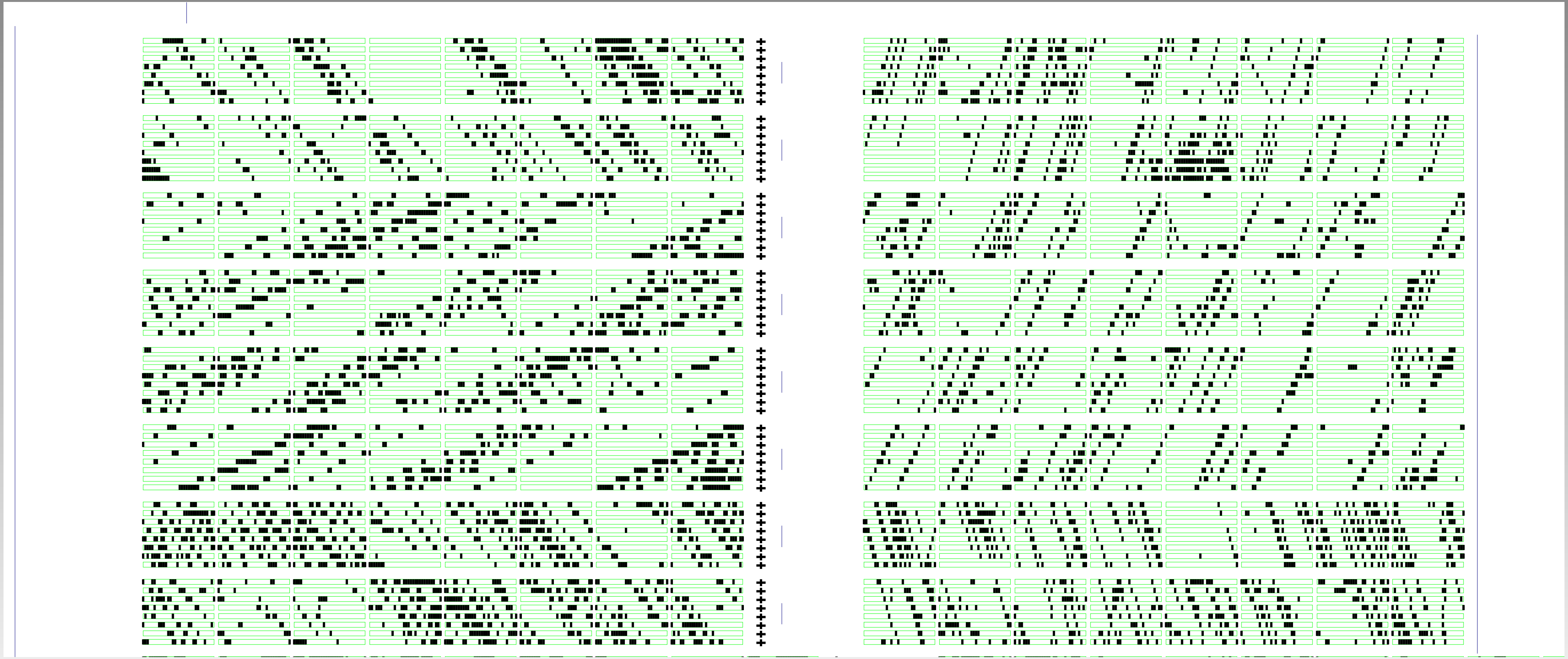
Y-projection

X-projection

Muon bundle event (geometry reconstruction)



A "record" muon bundle event



Y-projection

X-projection

Muon bundle event (geometry reconstruction)