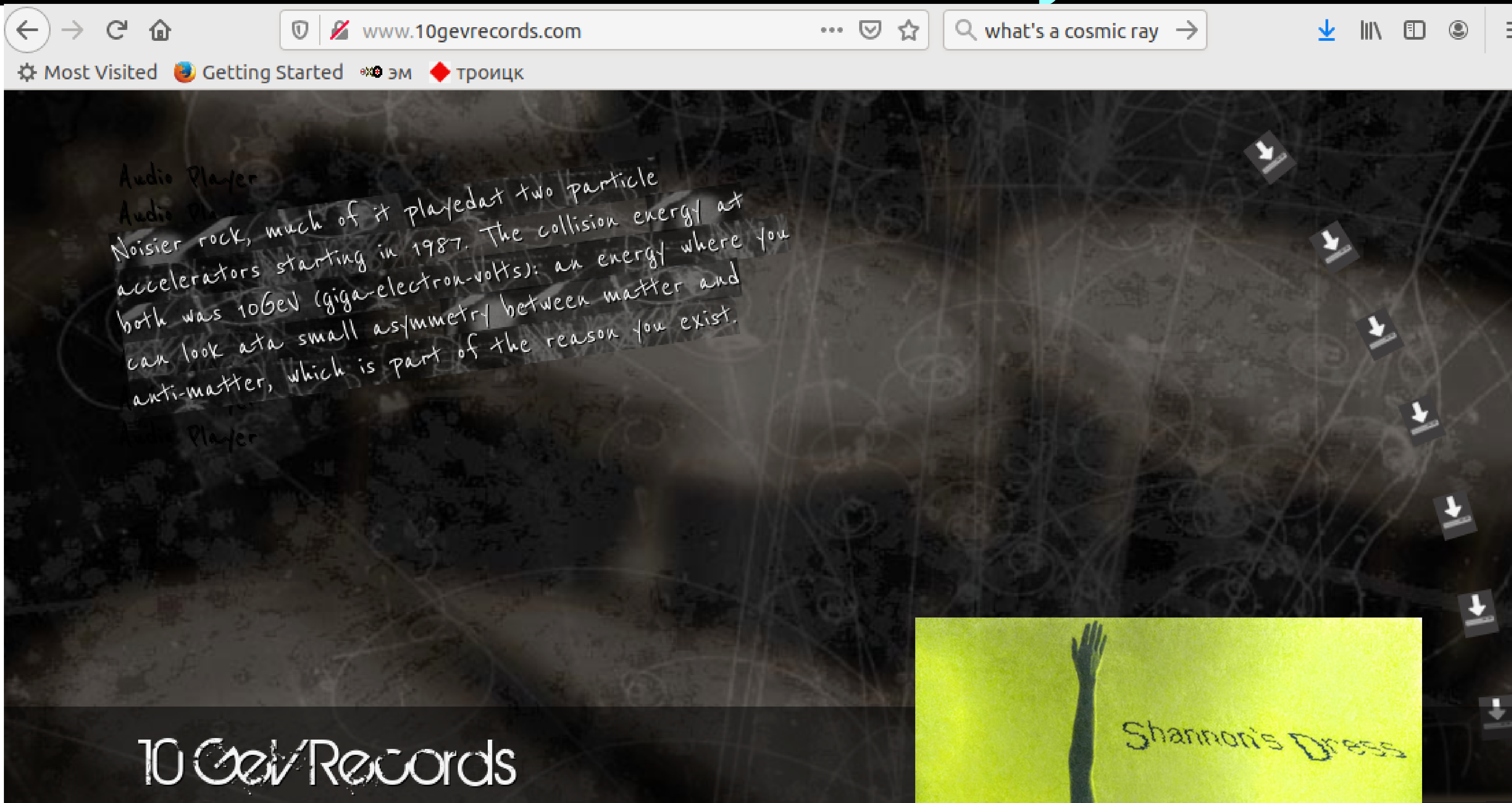
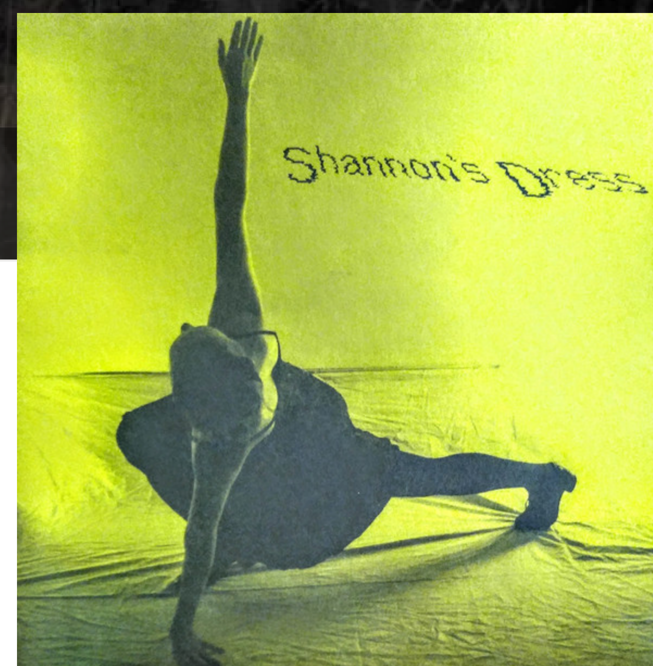
Taglines

- UHECR are out there
  - Lots of uses, aside from just astrophysics
- Local environment is typical
- Protons, gamma-rays, neutrinos
  - Primary vs. Secondary CR’s?
    - We really want the primary CR’s, but (except for direct measurements in space) get the secondaries on the ground!

But first - for the cynics





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?

(similar to basic questions of astronomy)

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?

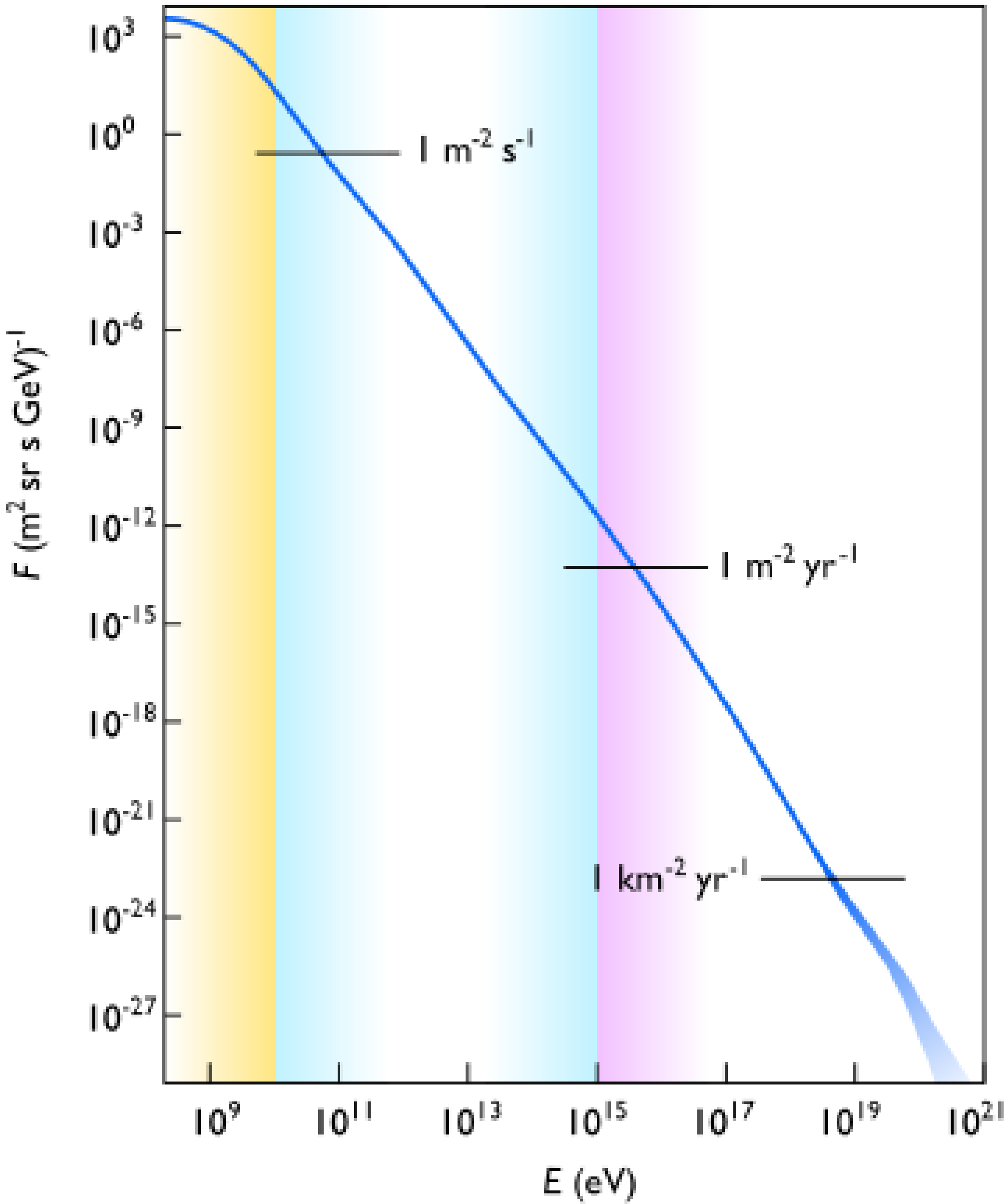
e.g., $dN/dE \sim E^{-\gamma}$: "power law"=>shock traversal

γ: "spectral index"

or could have multiple spectral indices=>multiple processes

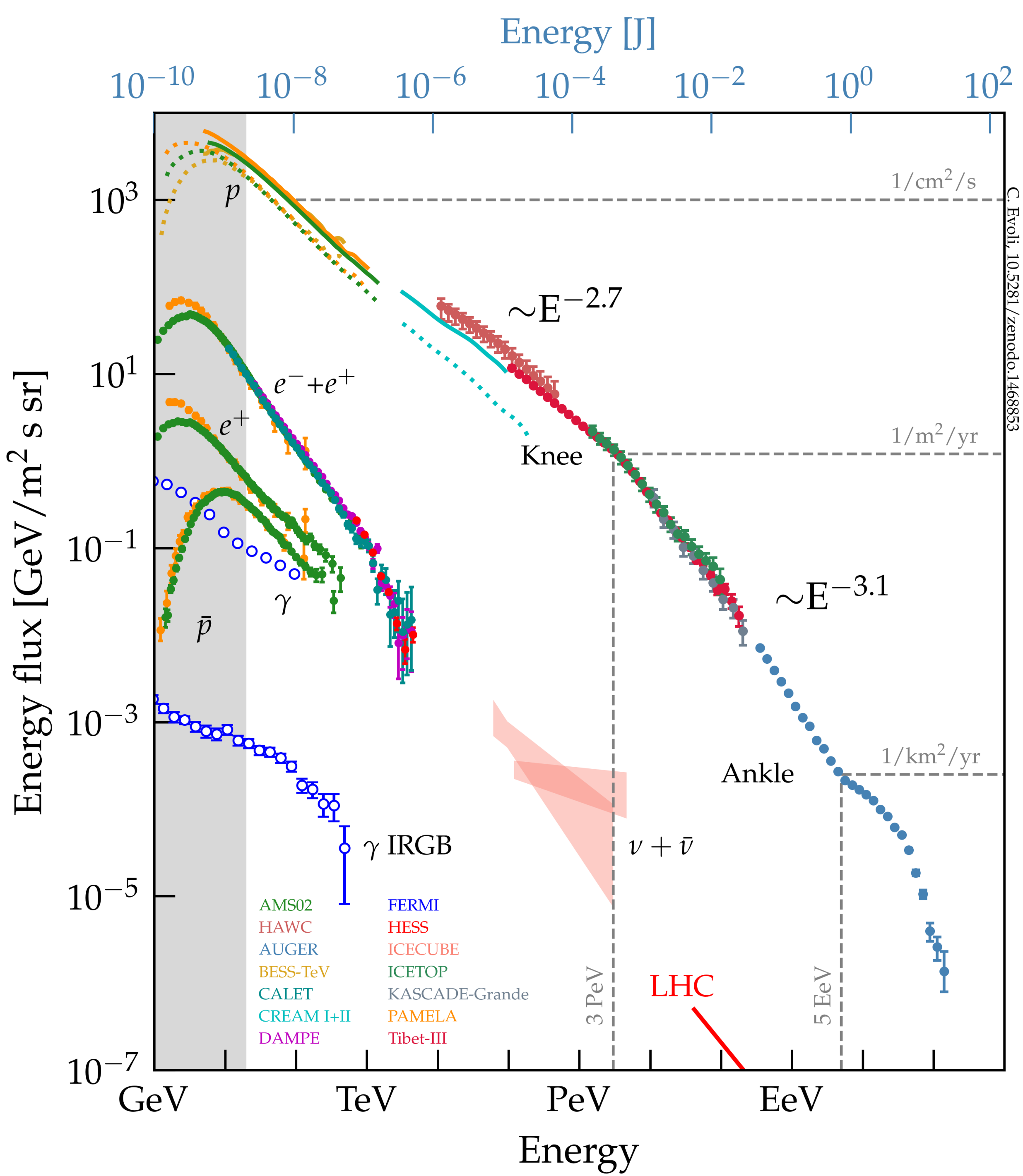
3) What is the angular distribution of the CR we measure, and do they point back (i.e., `cluster') to any particular source?

I.e.: want $dN/dEd\phi$ for each particle type



The charged cosmic ray energy spectrum at Earth ($dN_{charged}/dE$ only)

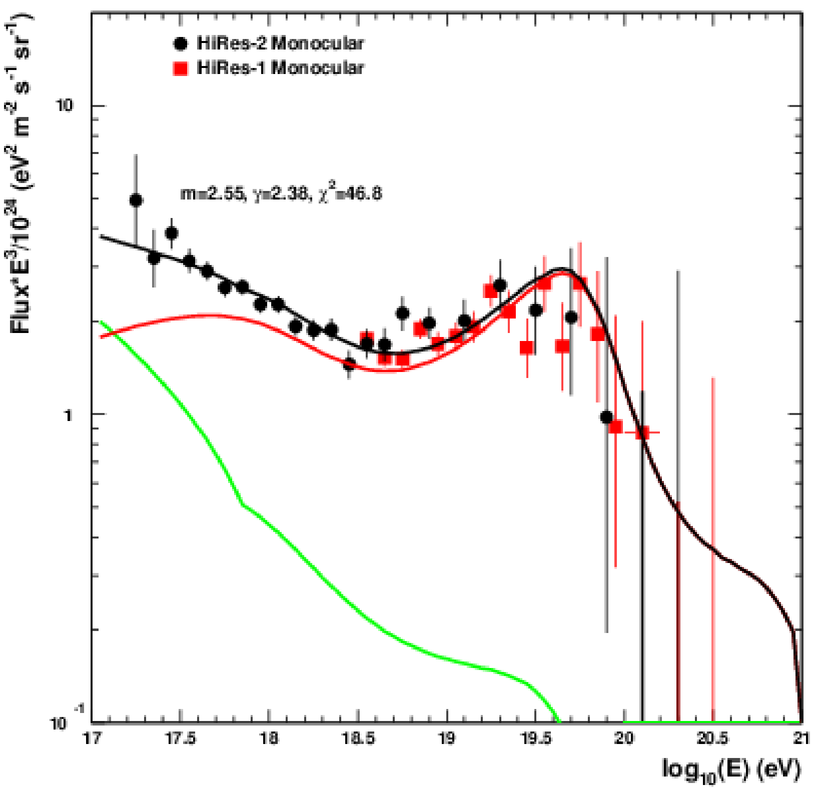
And overlaid with gamma-ray fluxes

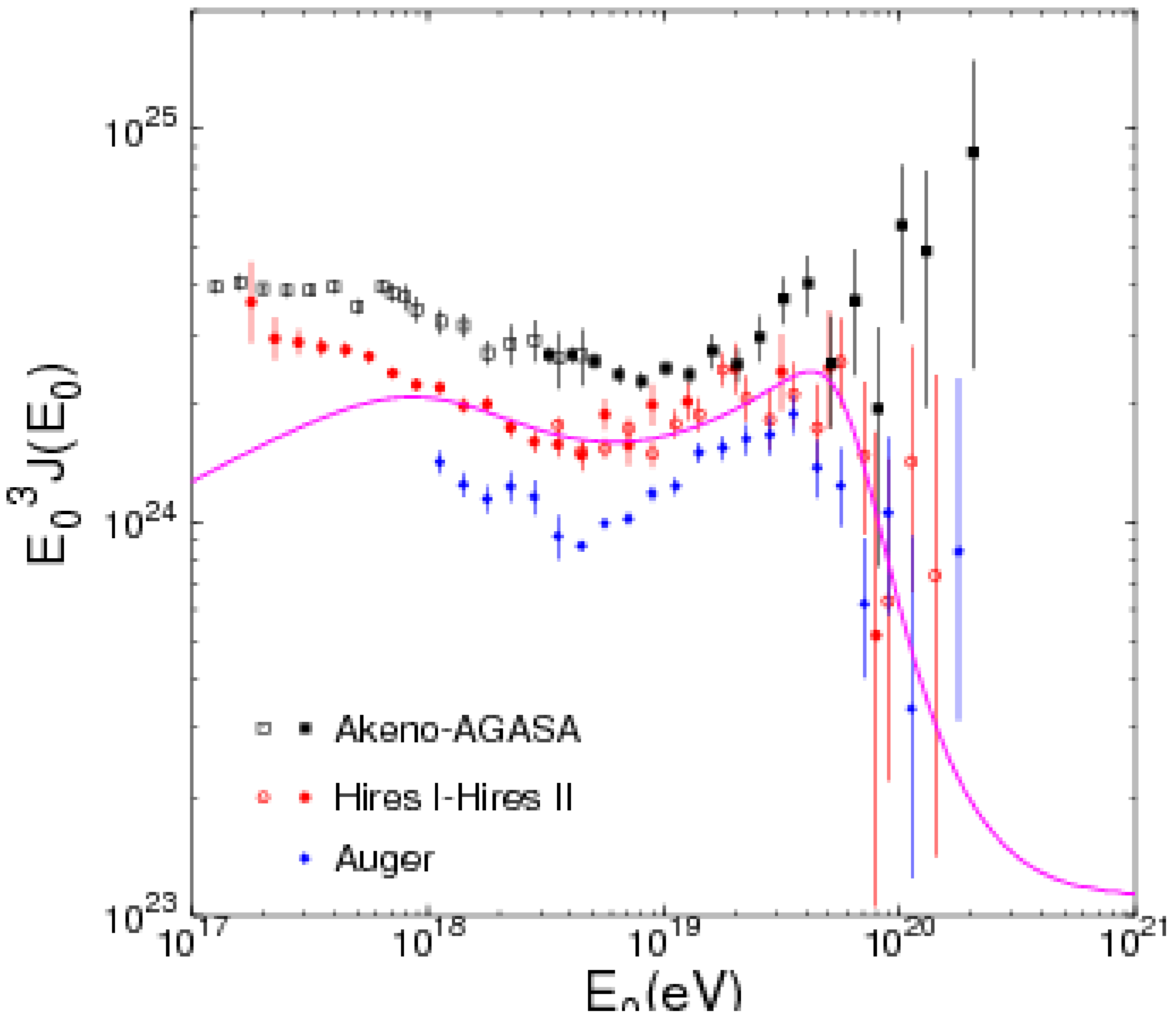


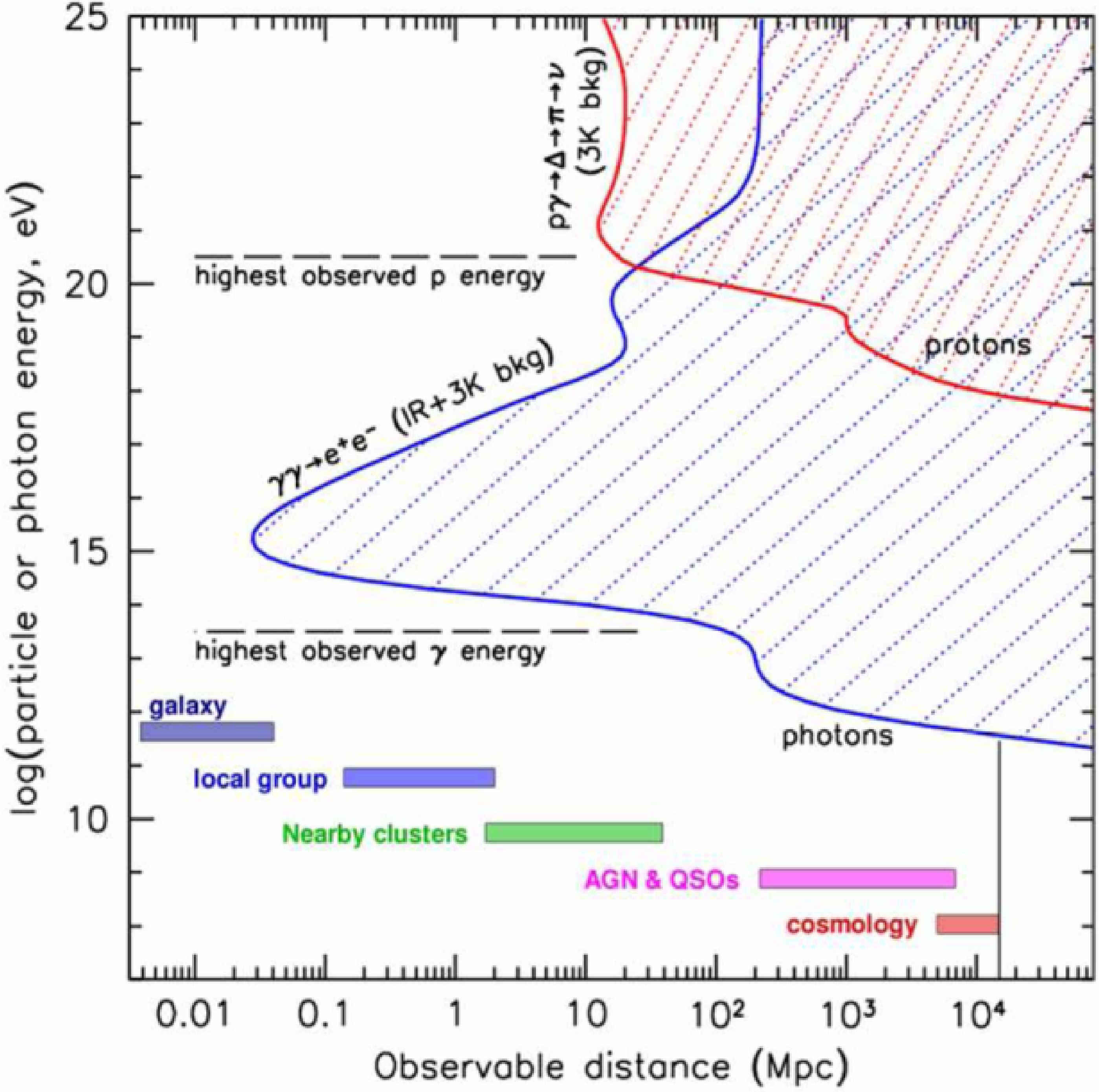
dN/dE for different particle types (including γ's!)

Spectral indices shown!

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

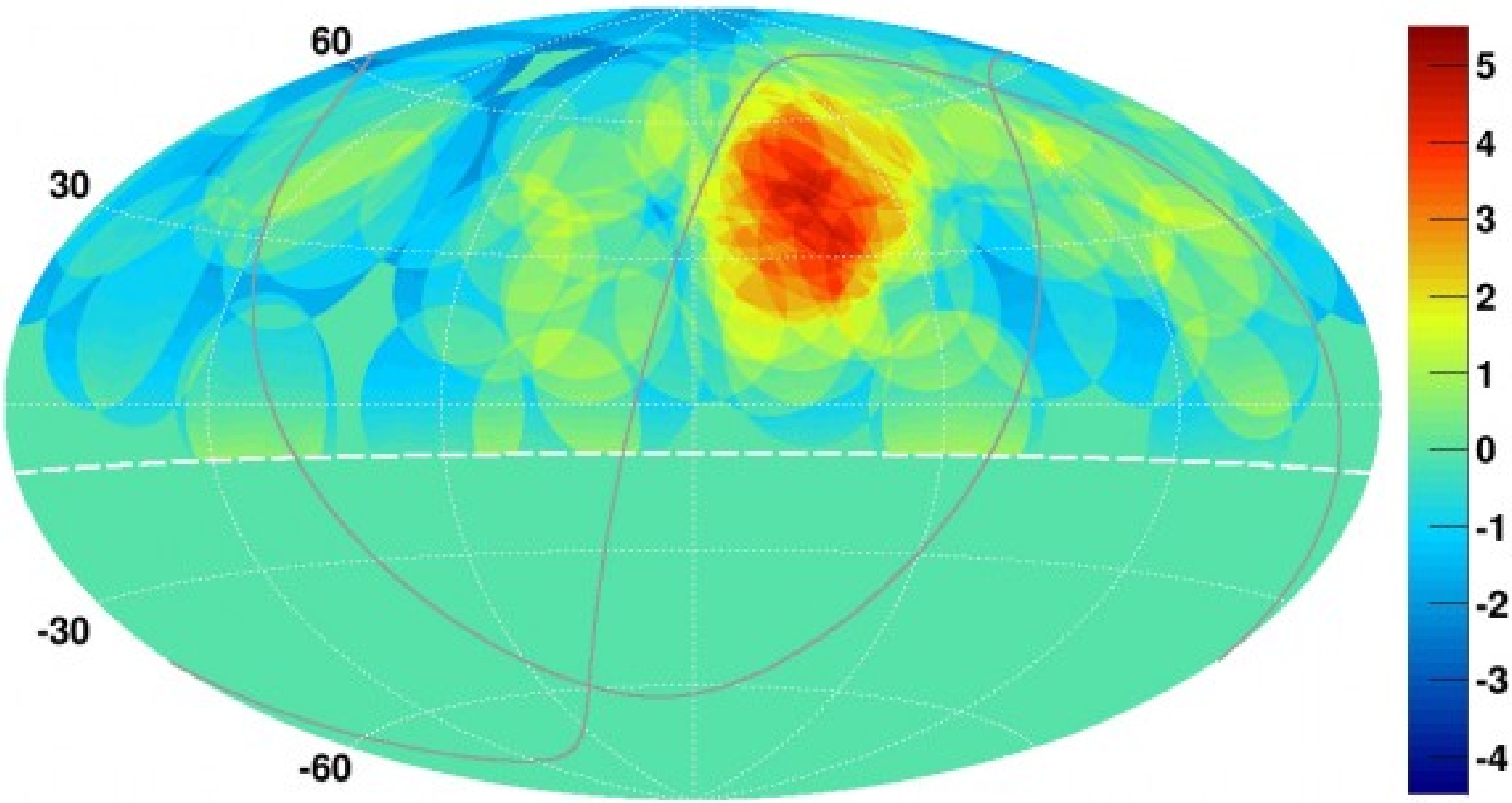




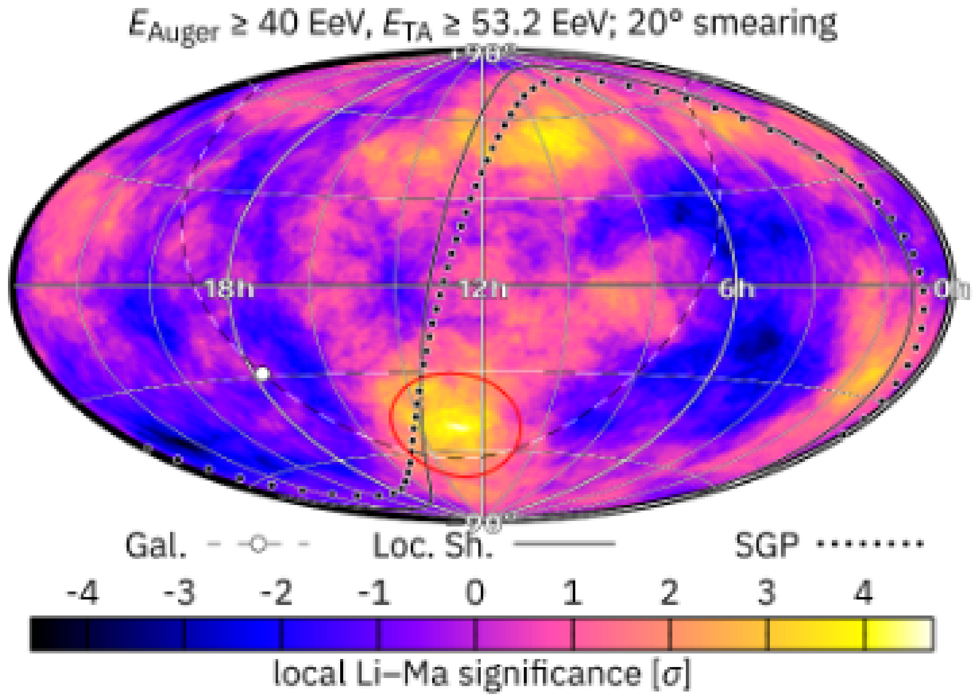


The Cosmic Microwave Background limits our ability to see into the Universe using protons and photons (but NOT neutrinos!)

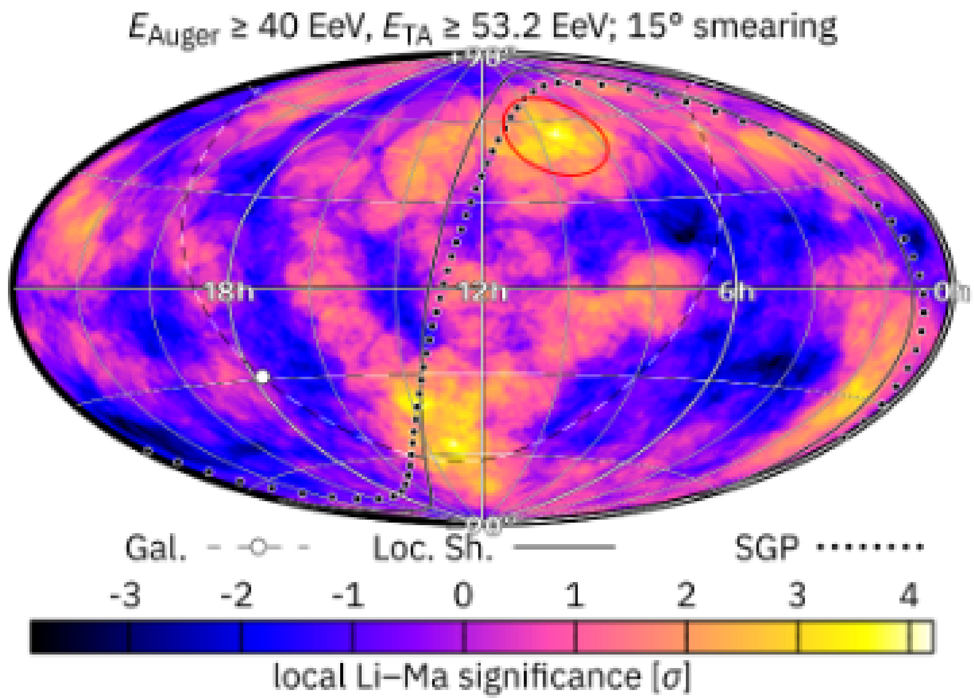
Or dN/dθdφ, E>57 EeV (TA, 2015)



Updated to 2019, combined Telescope Array + Auger

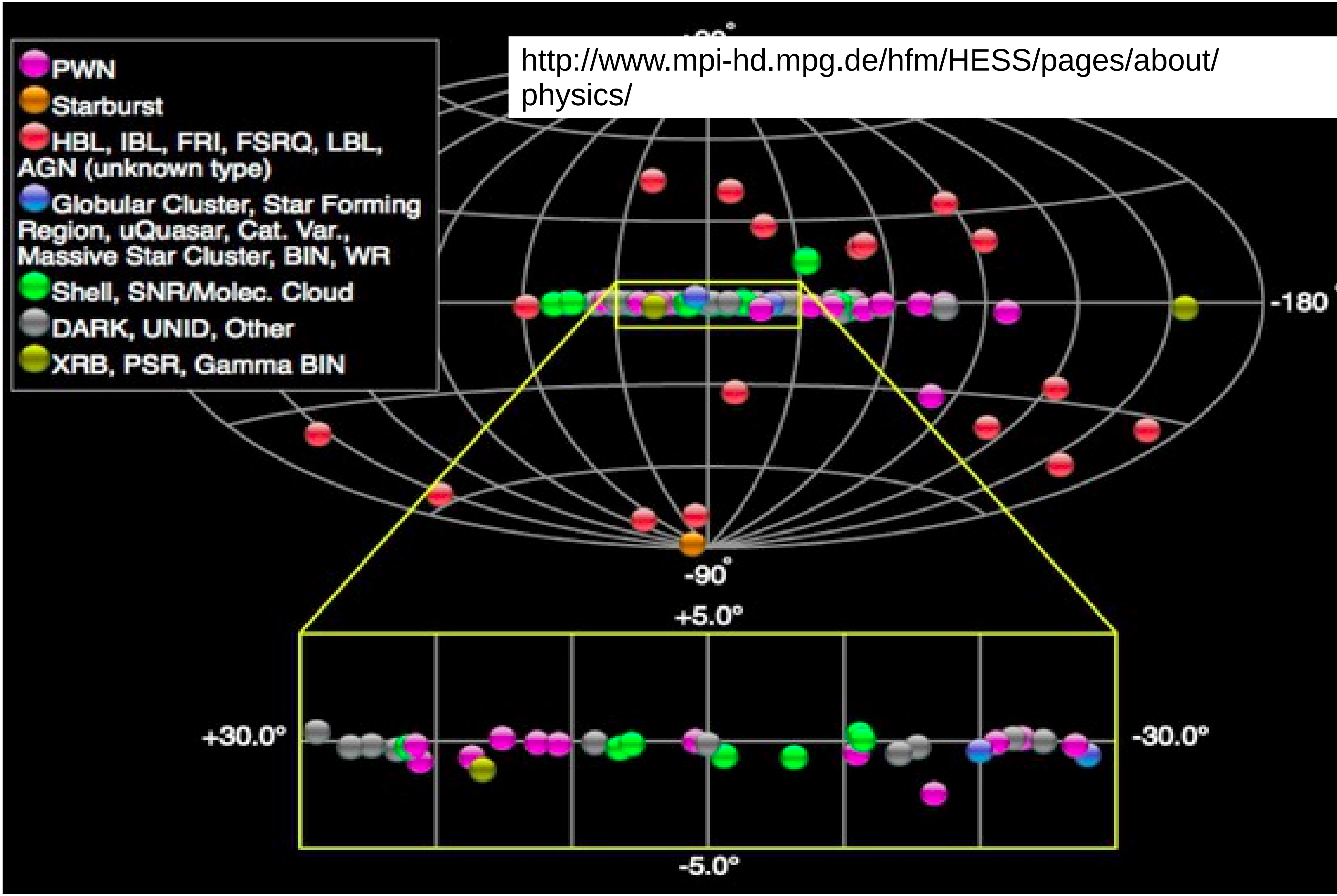


Significance



HESS VHE γ sources: $dN_\gamma /d\varphi d\theta$

http://www.mpi-hd.mpg.de/hfm/HESS/pages/about/physics/



Minimalists view of CR's

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

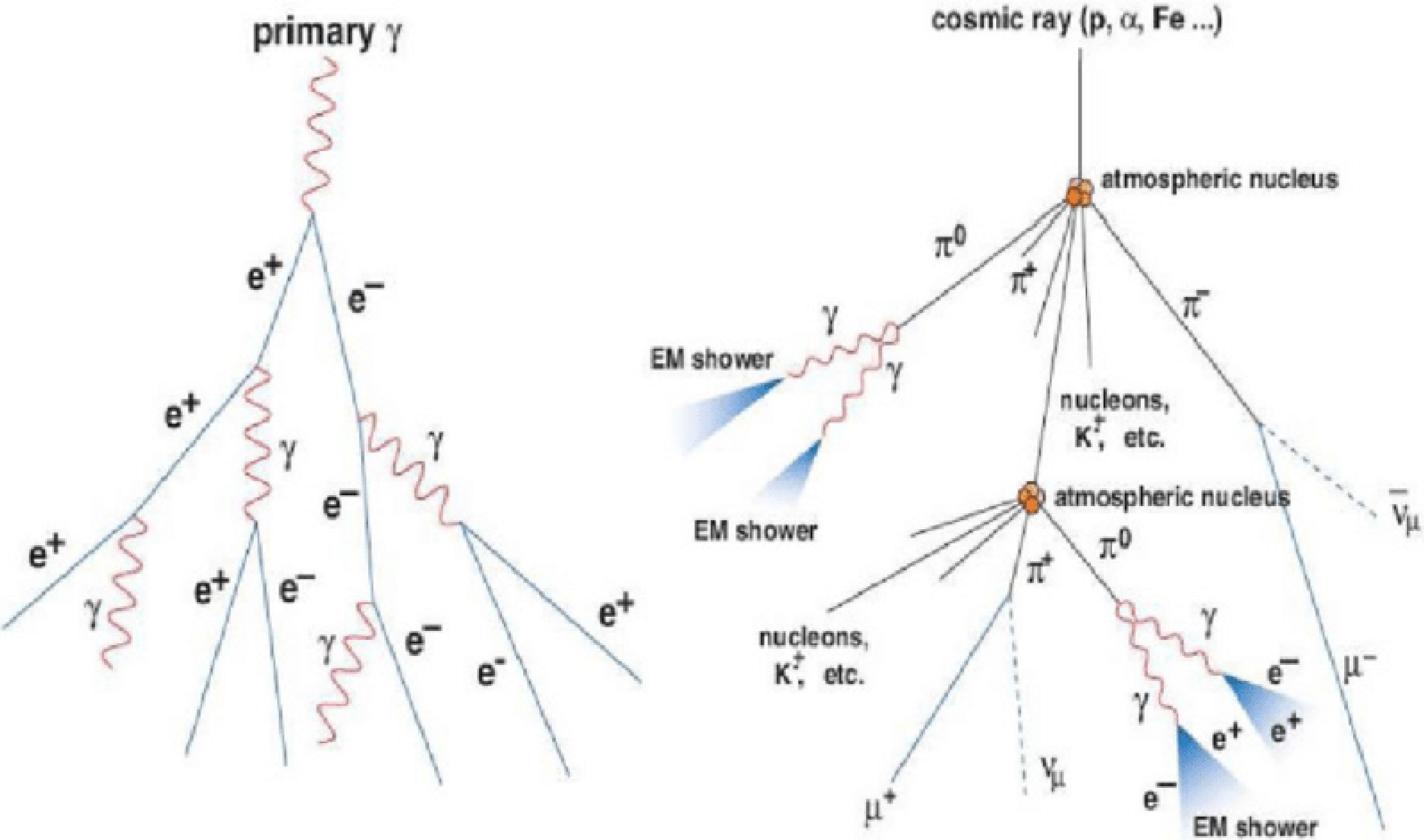
-photons similarly interact over cm (and even sub-cm)
length scales
(the paper to light trick)

a solar neutrino passes through about one light-year of
lead before interacting.

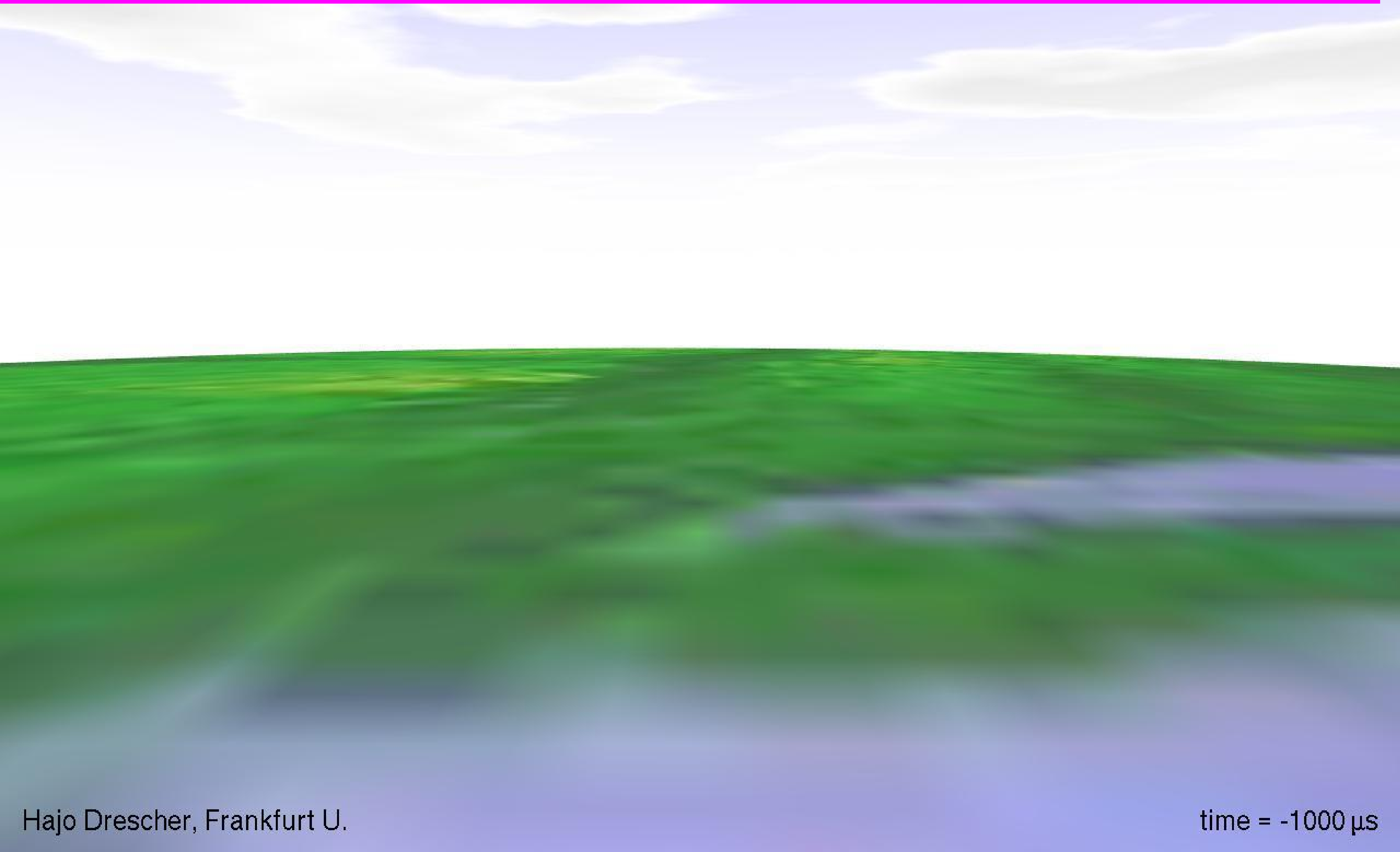
Punchline: protons/nuclei and gamma rays interact in the atmosphere and produce `**secondaries**' at the ground; neutrinos (generally) don't

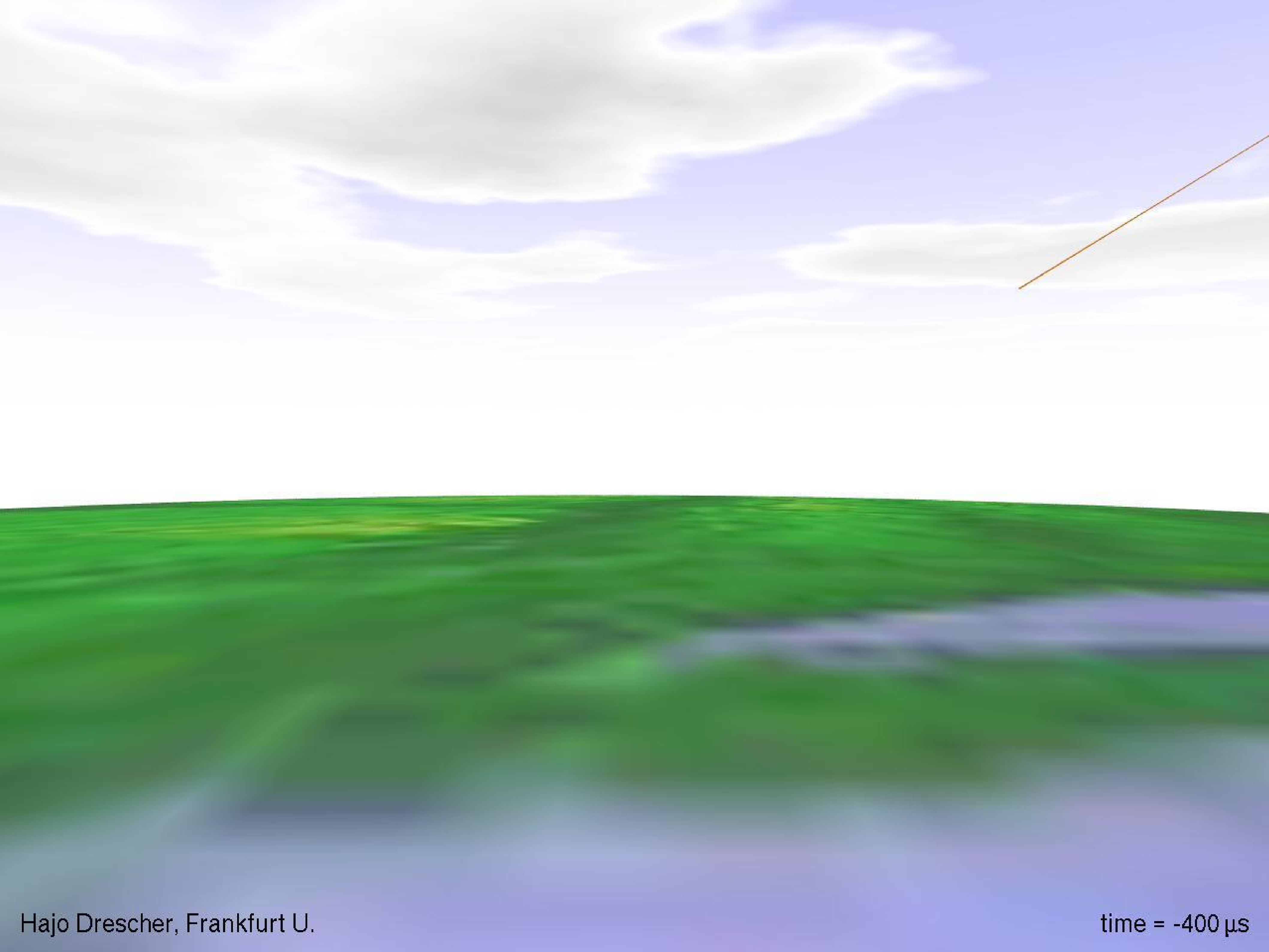
Primaries detected in-space

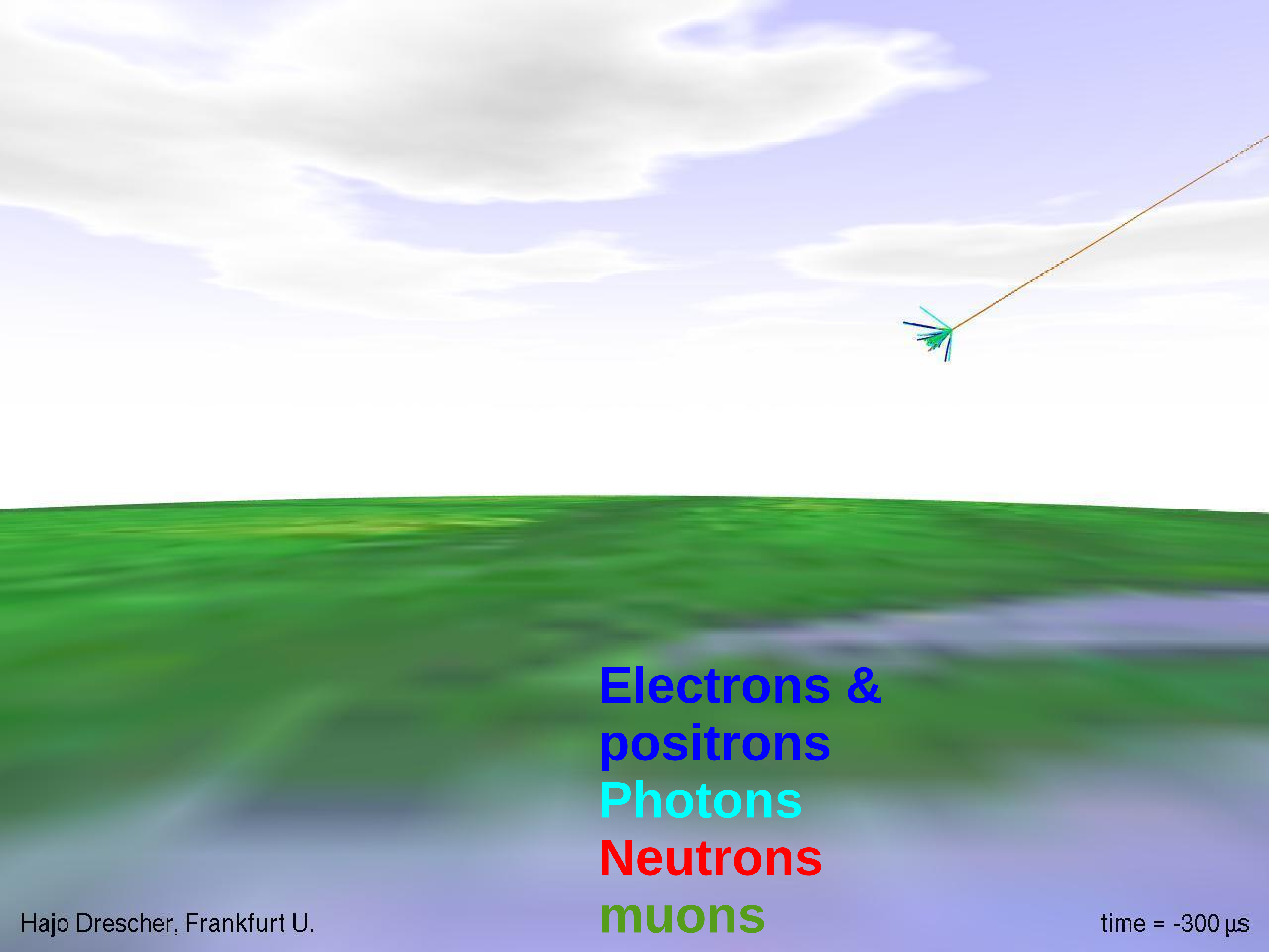
gamma vs. proton/He/Fe-induced

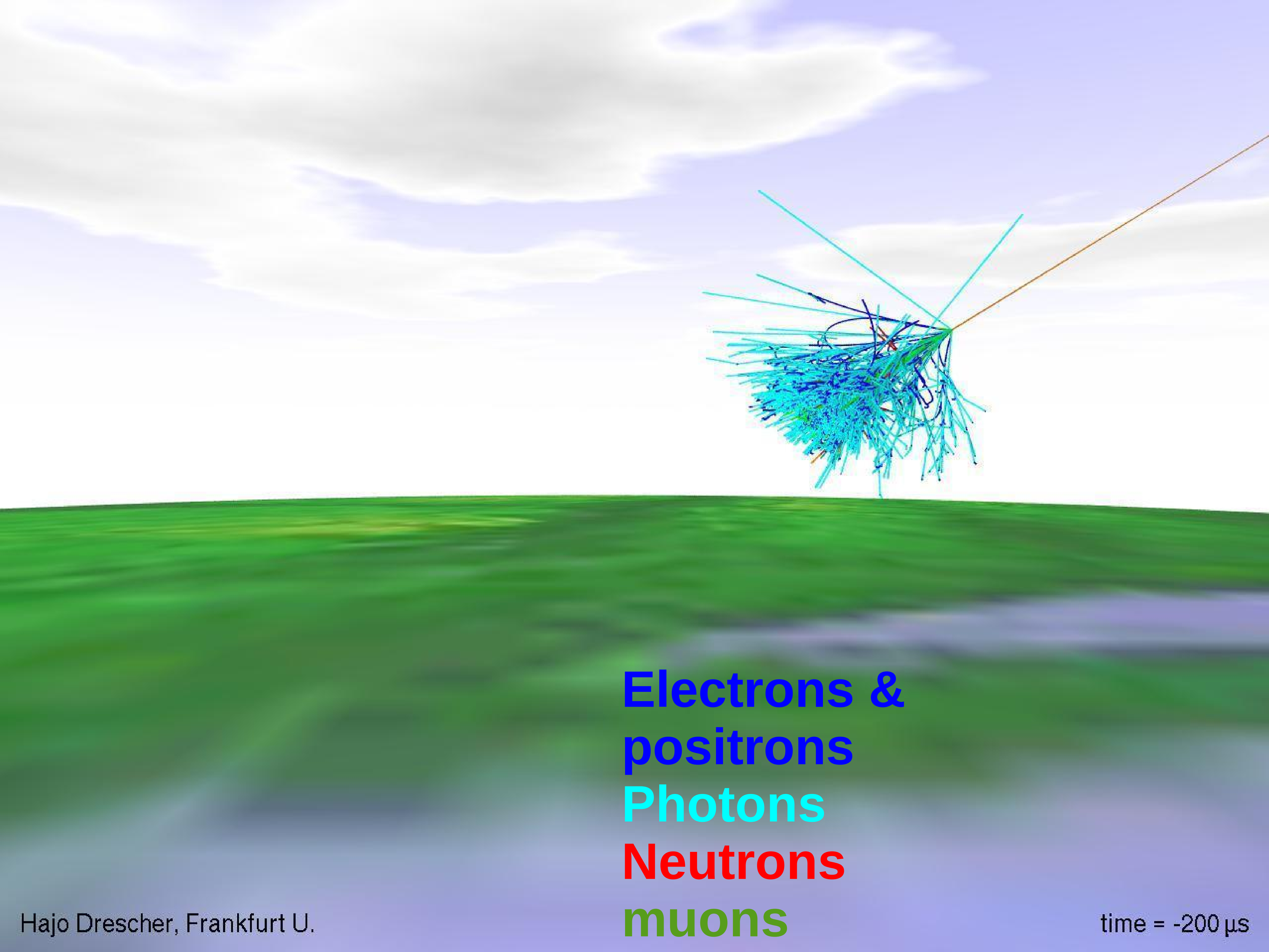


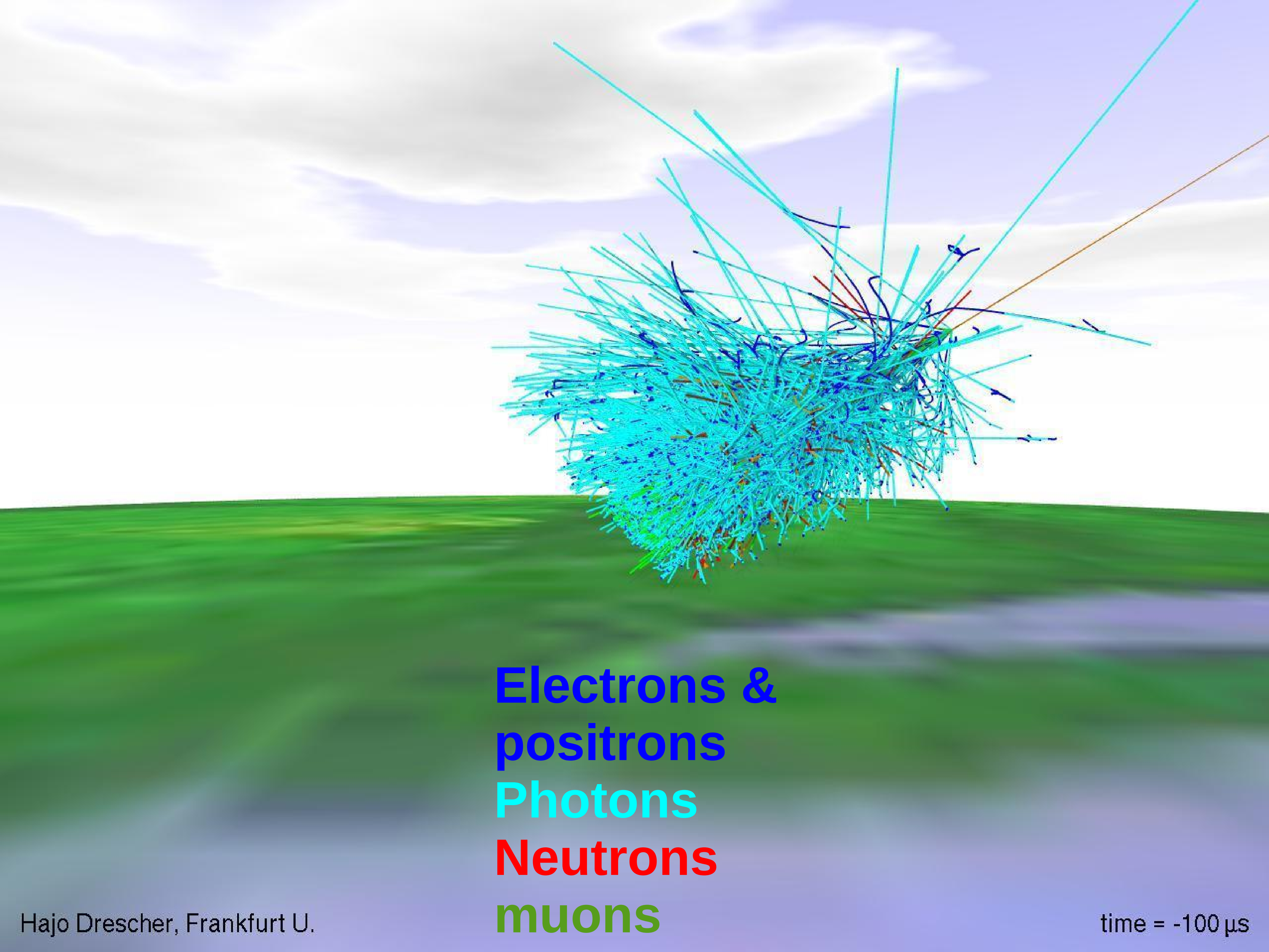
UHE proton detection: 1 J proton interacting in the upper atmosphere

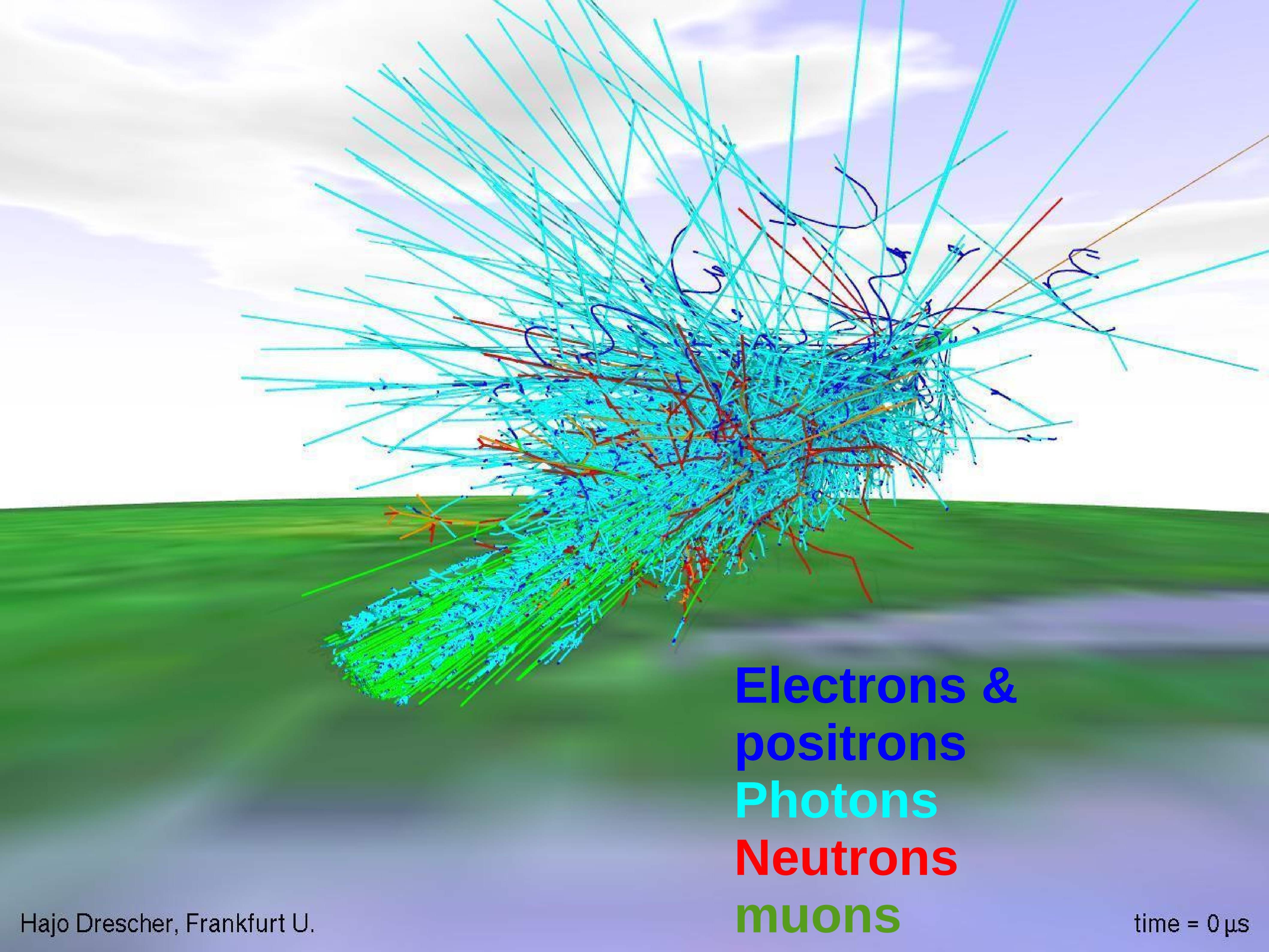


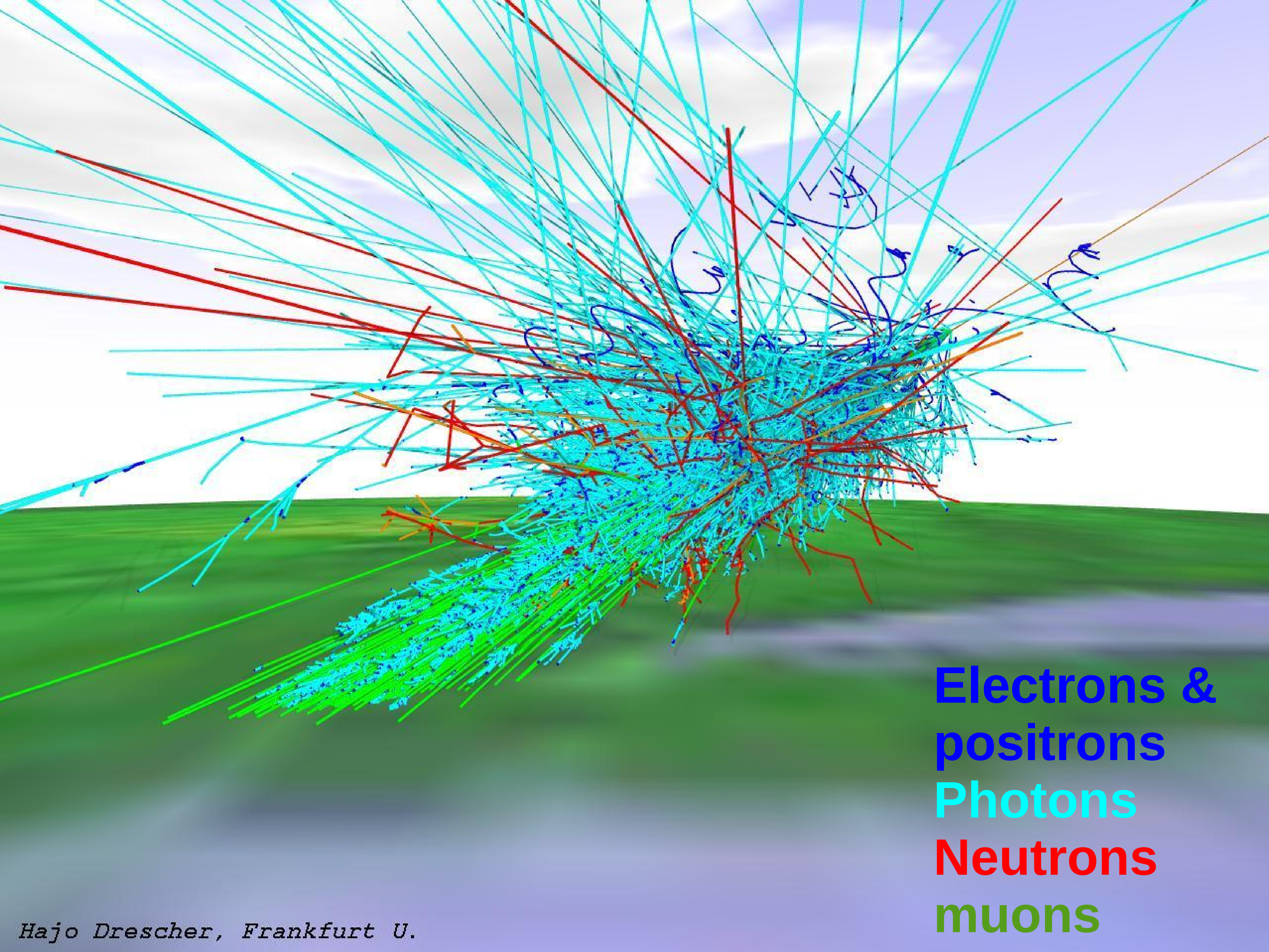

Hajo Drescher, Frankfurt U.
time = -400 µs

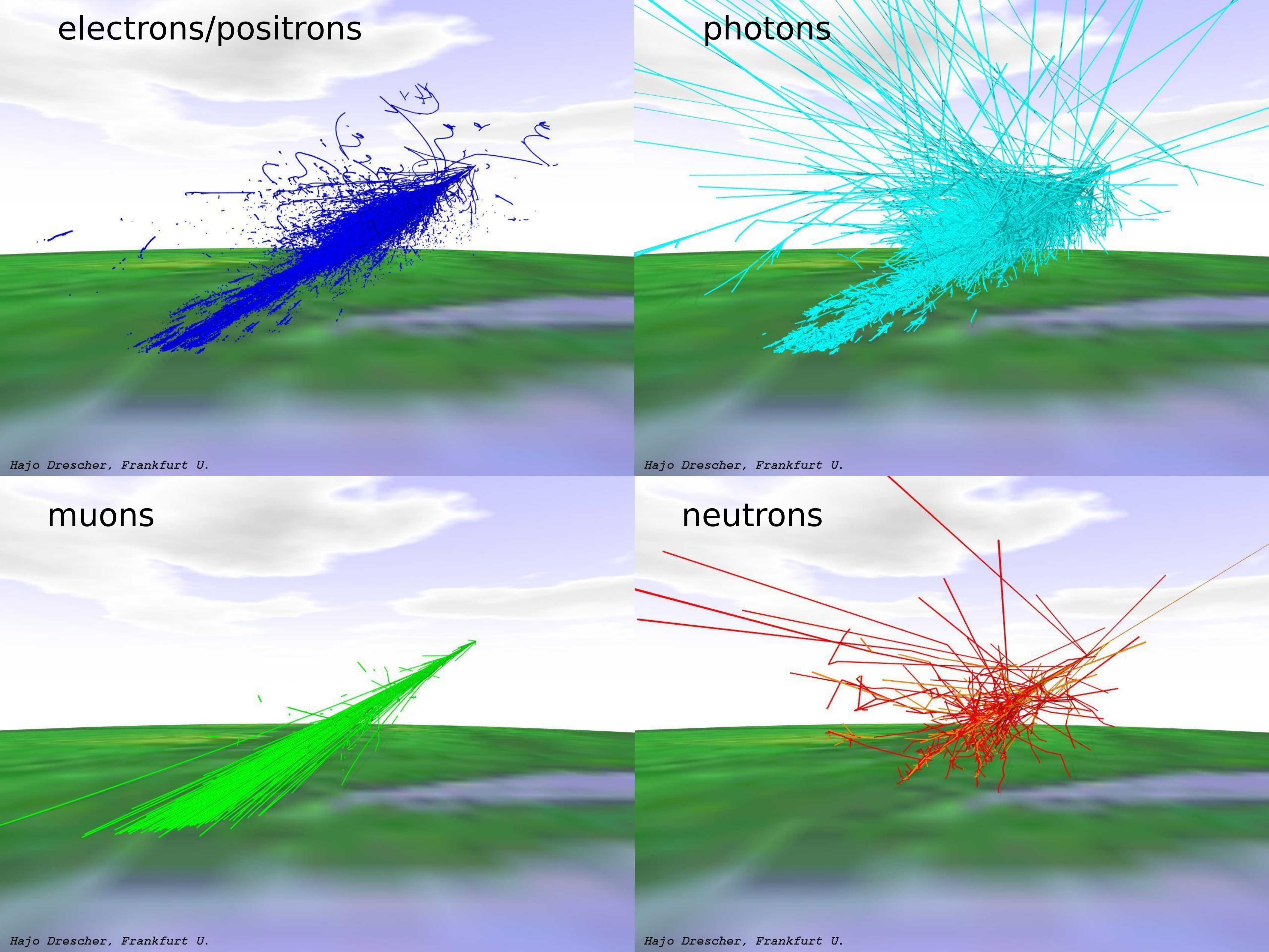

Electrons &
positrons
Photons
Neutrons
muons
Hajo Drescher, Frankfurt U.
time = -300 µs


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


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


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


Electrons &
positrons
Photons
Neutrons
muons
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.

How do we reconstruct the primary from the secondaries?

Limited number of possibilities:

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

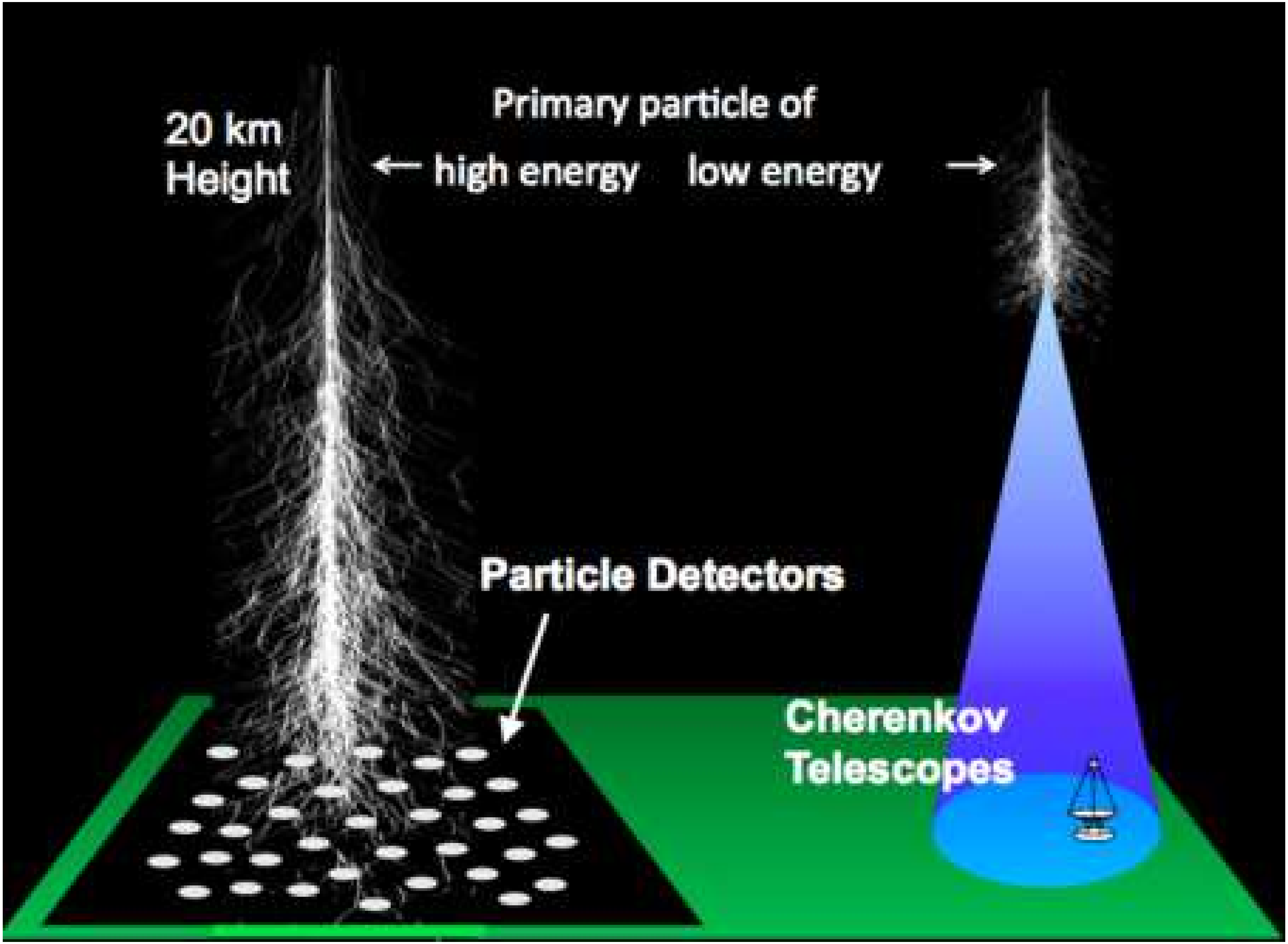
Includes fluorescence of nitrogen left in wake of shower

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

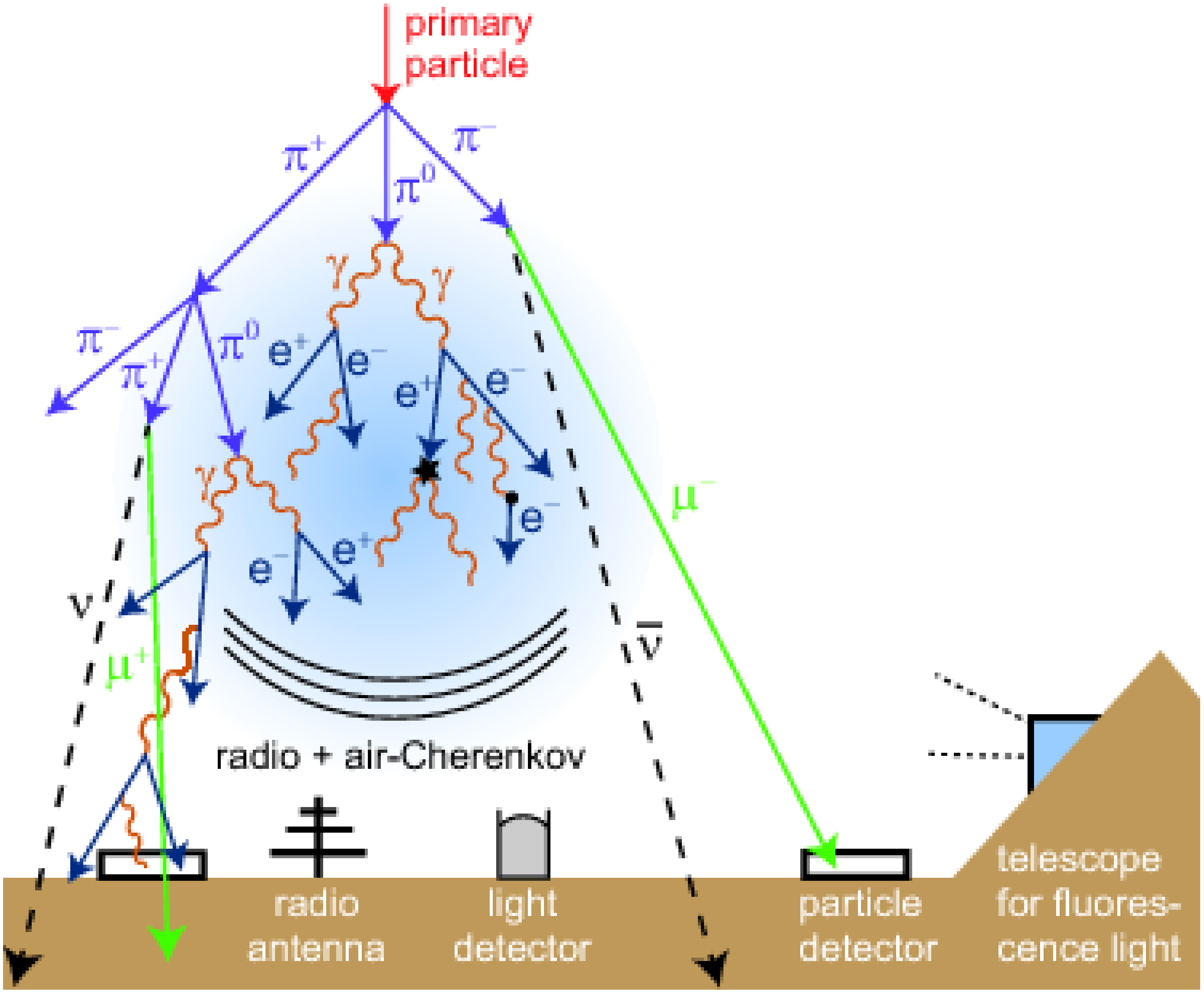
3) Measure the radio-frequency radiation (`geosynchrotron', e.g.) produced as charged particles in shower accelerate and bend in geomagnetic field

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)

gamma-detection, e.g.

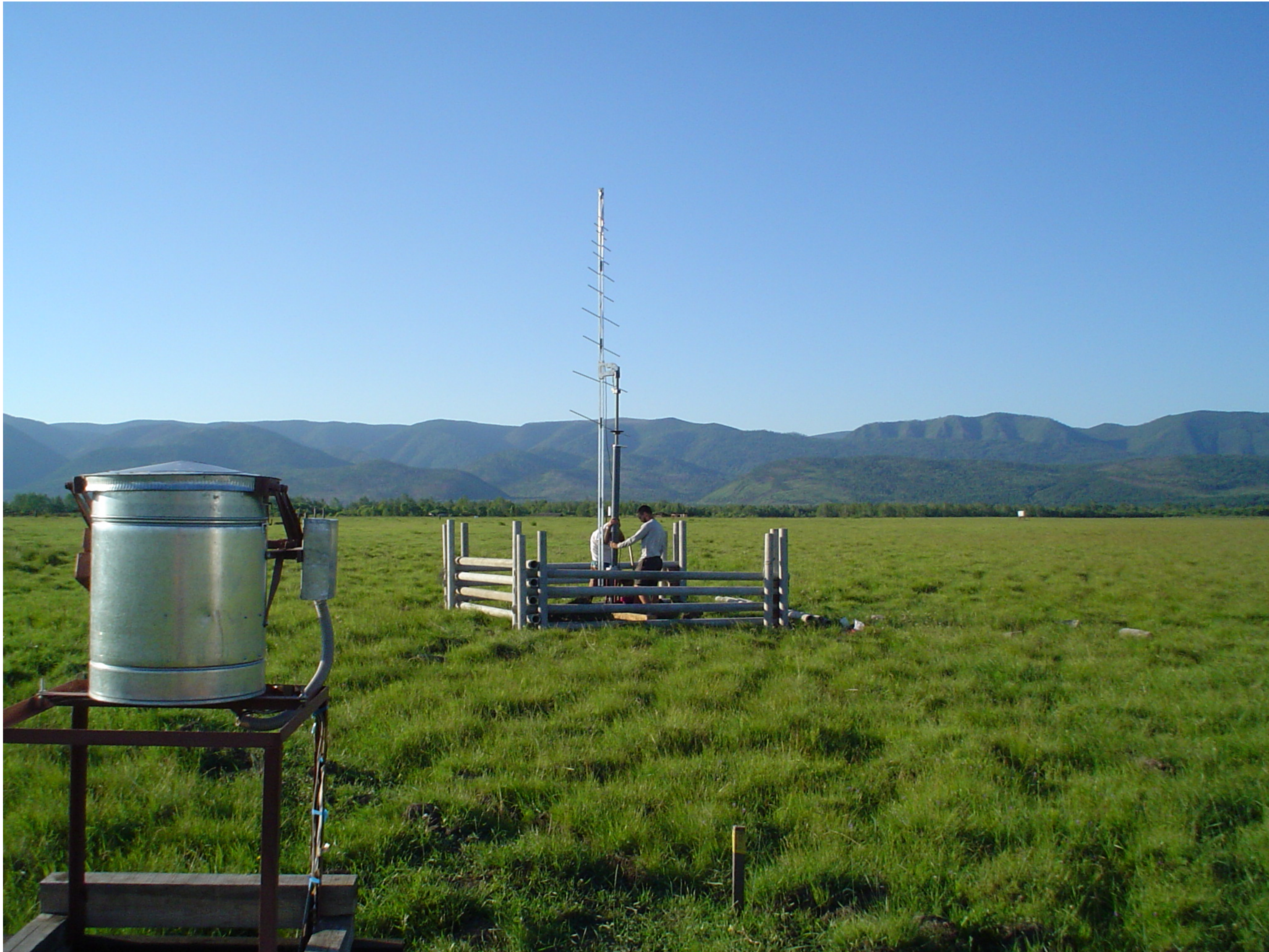


Charged Surface Detector arrays now include radio!



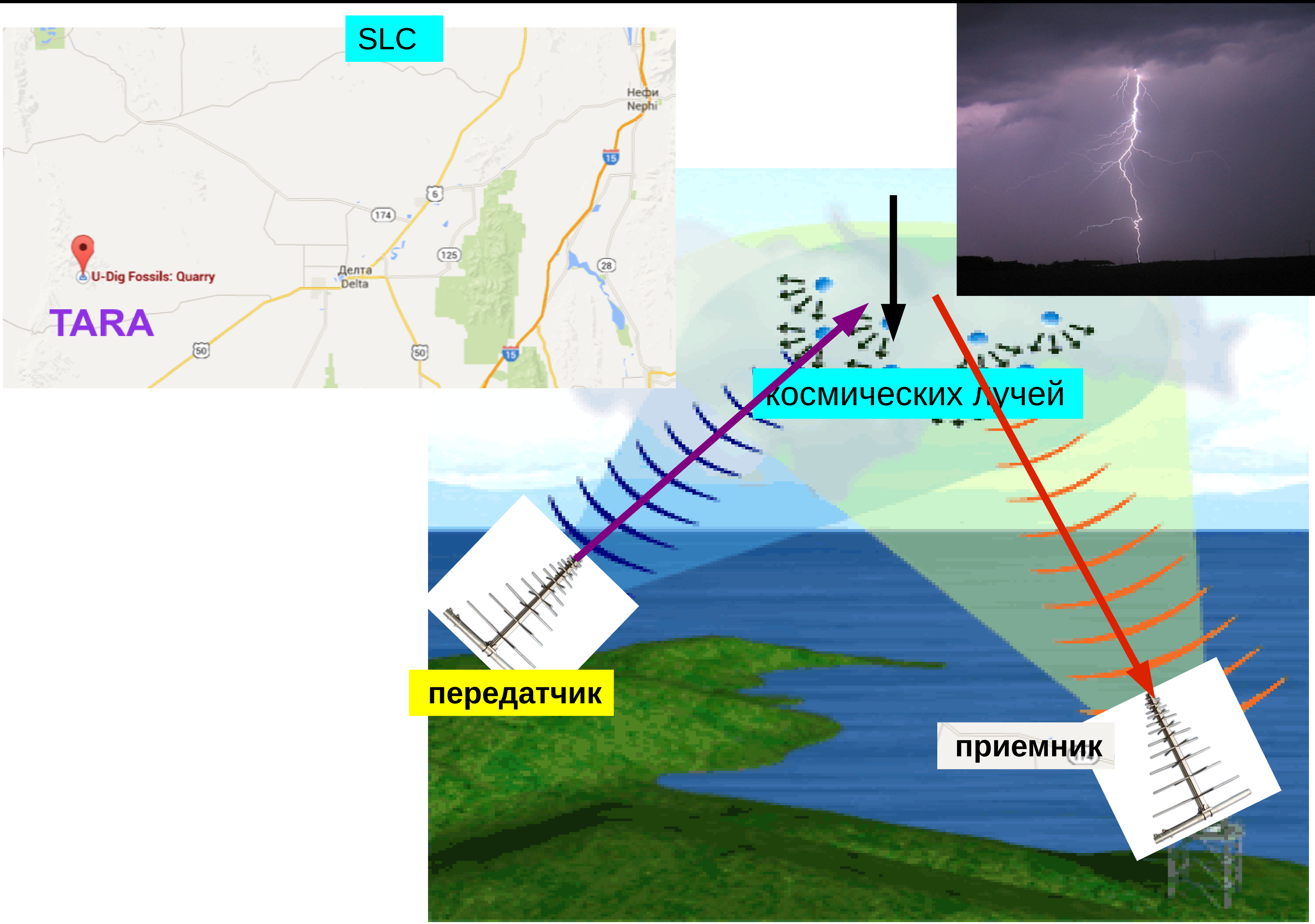
Radio component added to Auger water tanks


The TUNKA Experiment,
Siberia
THANKS
DOUG
&
NICKY




Rocky and Bullwinkle

Radar?


SLC
Нефи
Nephi
Делта
Delta
U-Dig Fossils: Quarry
TARA
космических лучей
передатчик
приемник

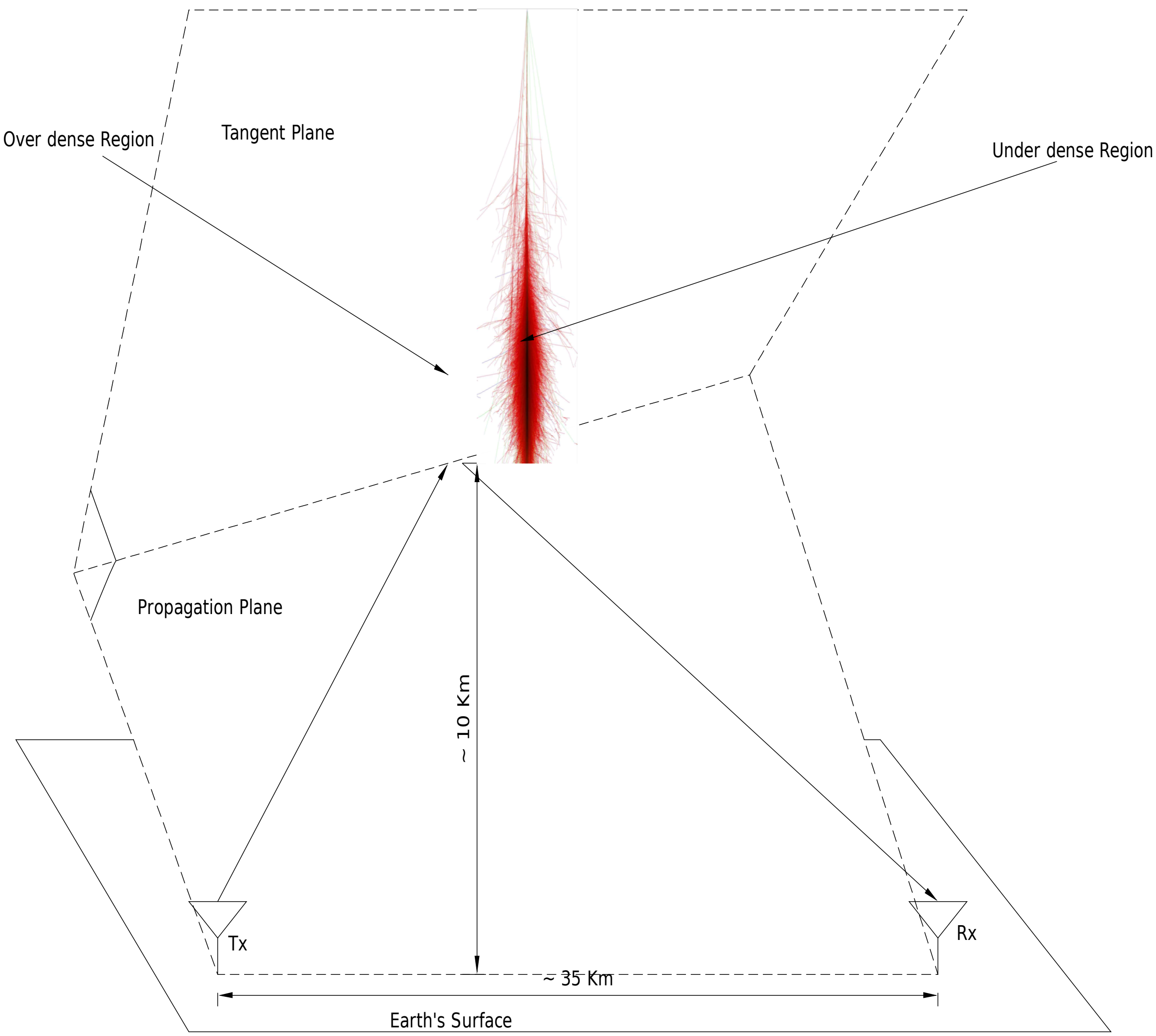
Bi – Static Radar

Cross – section?

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_{Tx}^2 R_{Rx}^2} = P_t G_t G_r \left[\frac{\sigma c^2}{(4\pi)^3 f^2 R_{Tx}^2 R_{Rx}^2} \right]$$

~~Under – dense($\nu > \nu_e$)~~

Fatal!



$$\nu_e = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}} \frac{1}{2\pi}$$

Over - dense ($\nu < \nu_e$)

Thin Wire approximation!

Physics

Plasma trail from EAS tail

Let the electrons experience transmitter **E**-field with CW *sounding frequency* $\omega = 2\pi\nu$:

$$m_e(\ddot{\vec{x}} + \gamma\dot{\vec{x}} + \omega_0^2\vec{x}) = -e\vec{E}\exp(-i\omega t) \tag{4}$$

$$\vec{p} = -e\vec{x} = \frac{e^2}{m}(\omega_0^2 - \omega^2 - i\omega\gamma)^{-1}\vec{E} \tag{5}$$

$$\frac{\vec{P}}{\epsilon_0\vec{E}} = \chi_e, \quad N, \quad \sum_i f_i = Z \tag{6}$$

$$\frac{\epsilon}{\epsilon_0} = 1 + \frac{Ne^2}{\epsilon_0 m_e}\sum_j f_j(\omega_0^2 - \omega^2 - i\omega\gamma)^{-1} \tag{7}$$

High-frequency limit

Let $\omega \gg \omega_j$. We have

$$\frac{\epsilon}{\epsilon_0} = 1 - \frac{ZNe^2}{\epsilon_0 m_e}\omega^{-2} \tag{8}$$

$$\omega_p^2 = \frac{ZNe^2}{\epsilon_0 m_e} \tag{9}$$

$$n_e = NZ \tag{10}$$

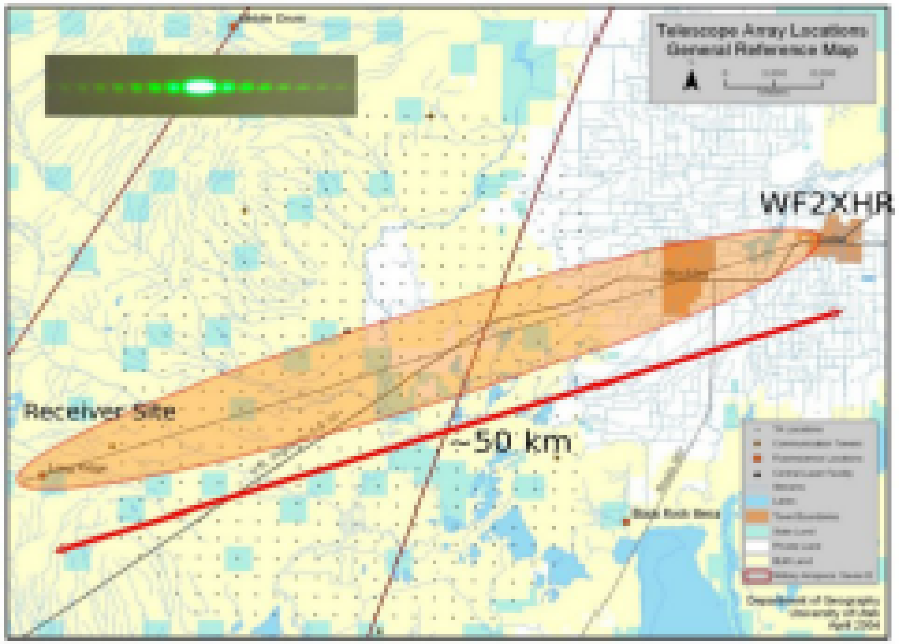
$$\boxed{\nu_p = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}} \tag{11}$$

Terminology:

If $\nu < \nu_p$, the shower trail is over-dense. If $\nu > \nu_p$, then the shower trail is under-dense.

Goal of TARA

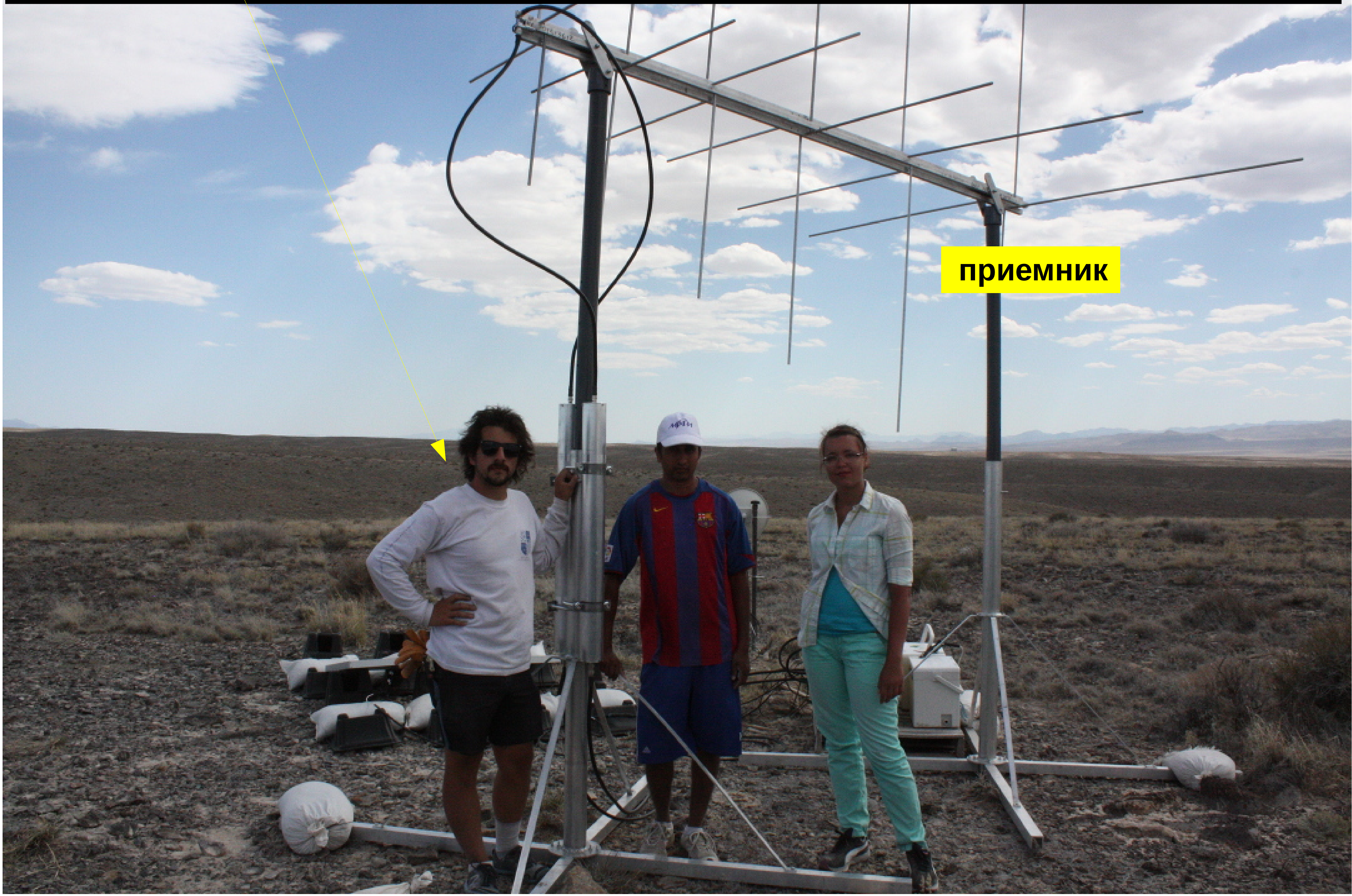
- TARA aims to reduce costs of detecting the highest energy cosmic rays
- Bi-static radar system situated above Telescope Array (TA) surface detector (SD)
- Receiver co-located with Long-ridge fluorescence detector (FD)
- Situated to allow for coincidence studies



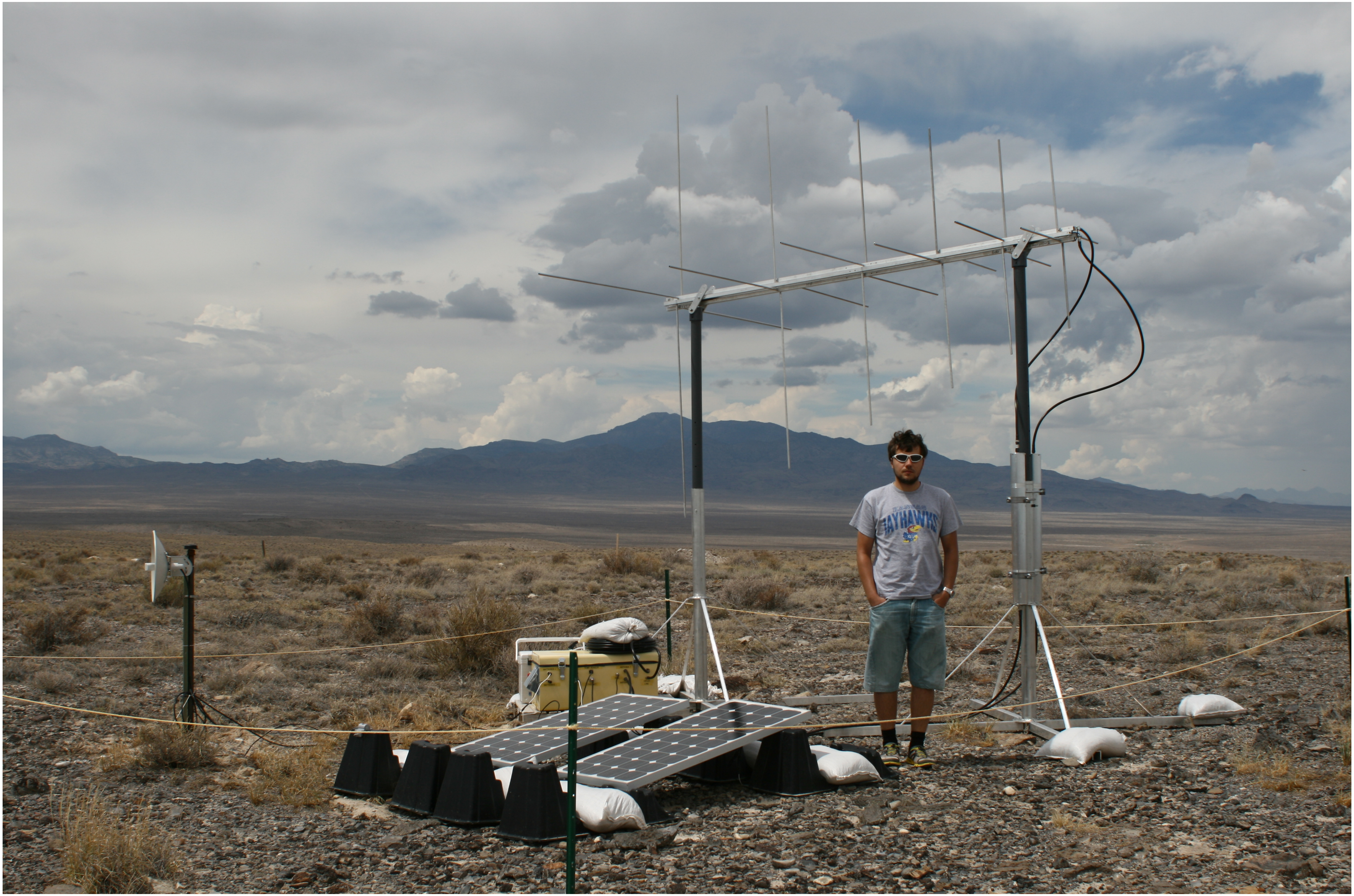
Ballpark figures.

Exp.	TA	PAO	TARA
Cost (Mill. USD)	50	150	1.5
Stations/Units	500	1600	2
Energy Threshold (EeV)	10 (excluding TALE)	1 (hybrid)	10
Surface Area (km^2)	800	3000	200
(km^2)/(Mill. USD)	20	20	100

Steven, Sam and Марина (28.06.14)



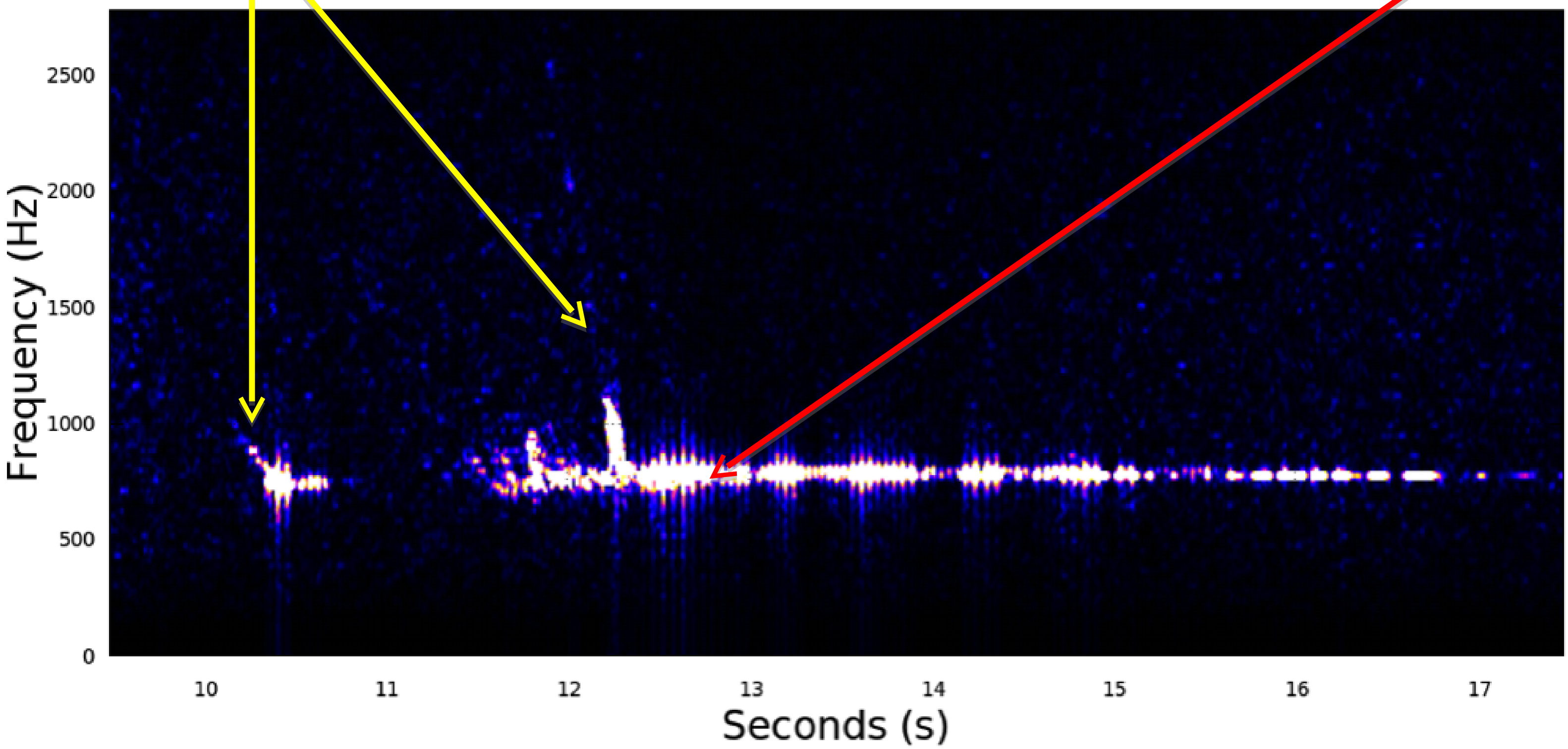
Саша (18.08.14) (ремонт)



TARA Meteorite (80 km elevation; no LOS)

Head Echo (~ Shower Front)

Trail Echo (~ Ionization Trail)



Tx : TARA Utah Back lobe

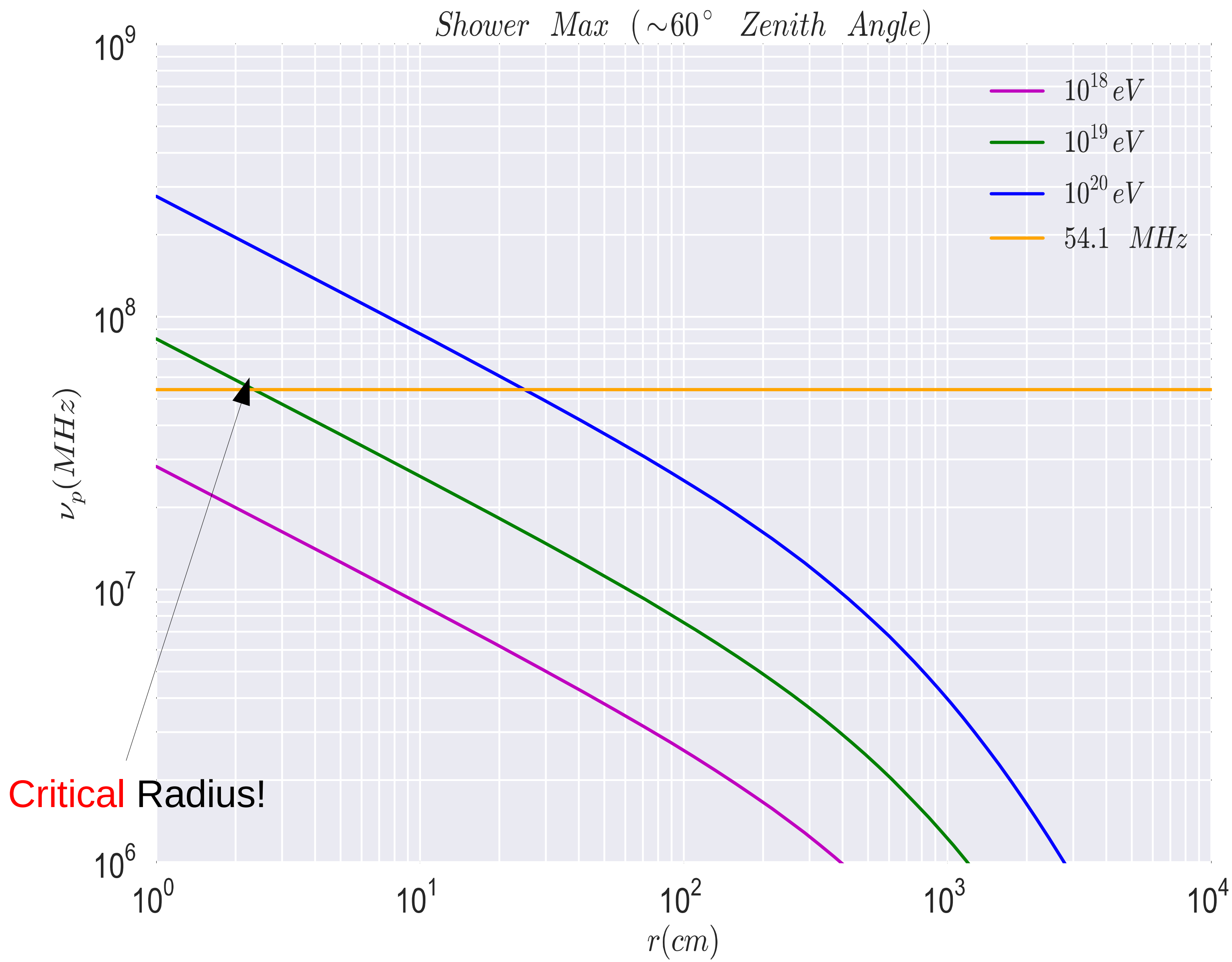
Rx : Lawrence, KS

1600 km

Need plasma frequency above 54.1 MHz carrier

~~Under - dense($\nu > \nu_e$)~~
Fatal!

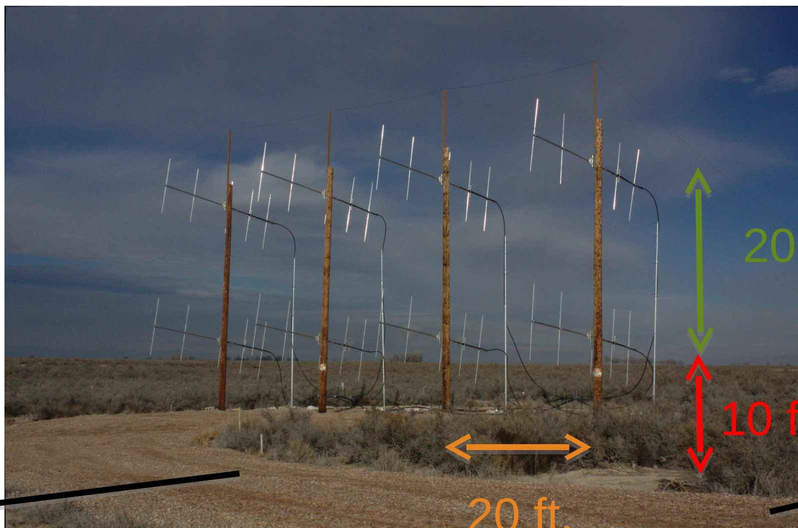
Over - dense ($\nu < \nu_e$)
Thin Wire approximation!



Transmitter

~ 20 – 40 KW at *54.1 MHz*

Phased Yagi Array



39 km to receiver

100 ft.

Power Amplifier

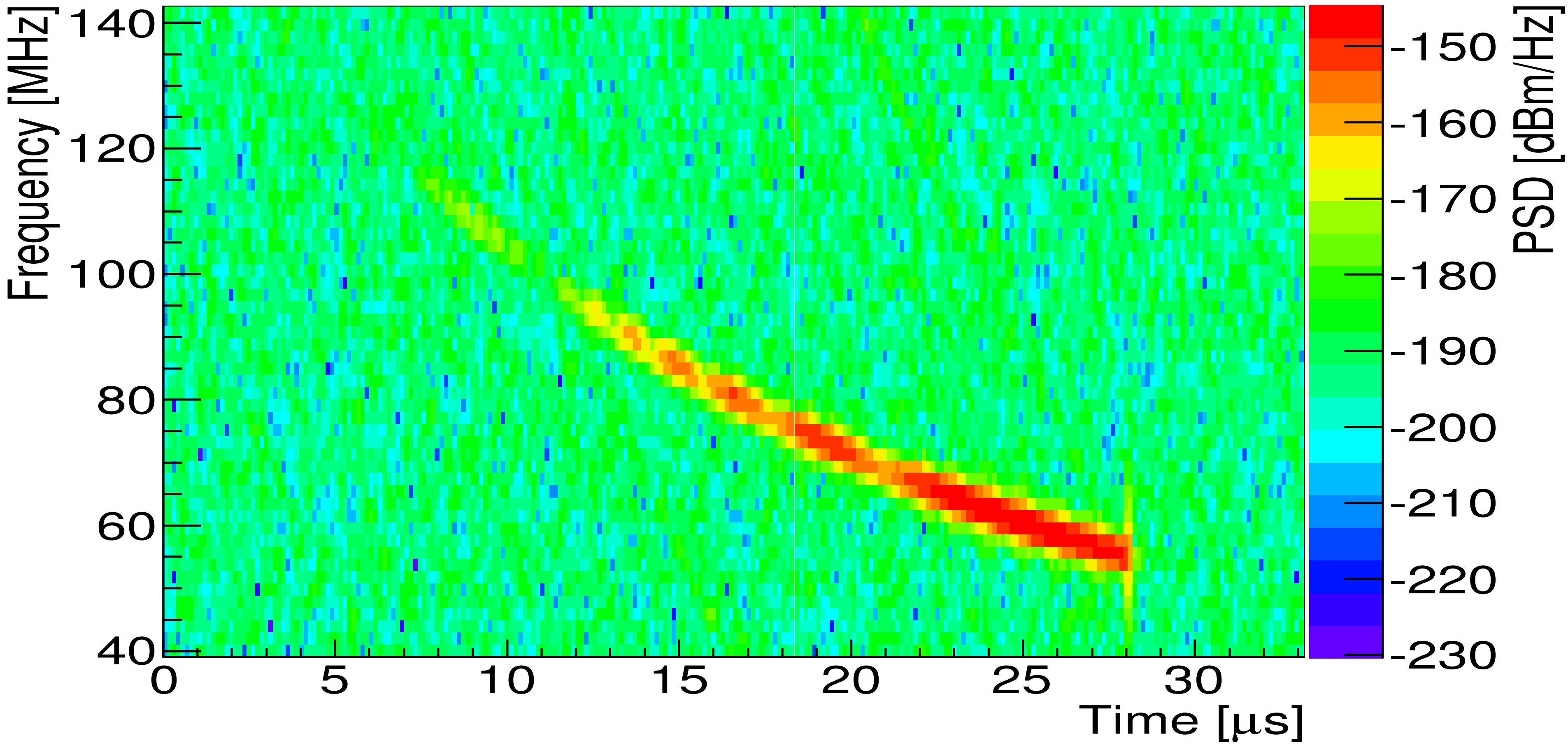
Filters

KUTV(20 KW)

KTVN (20KW)

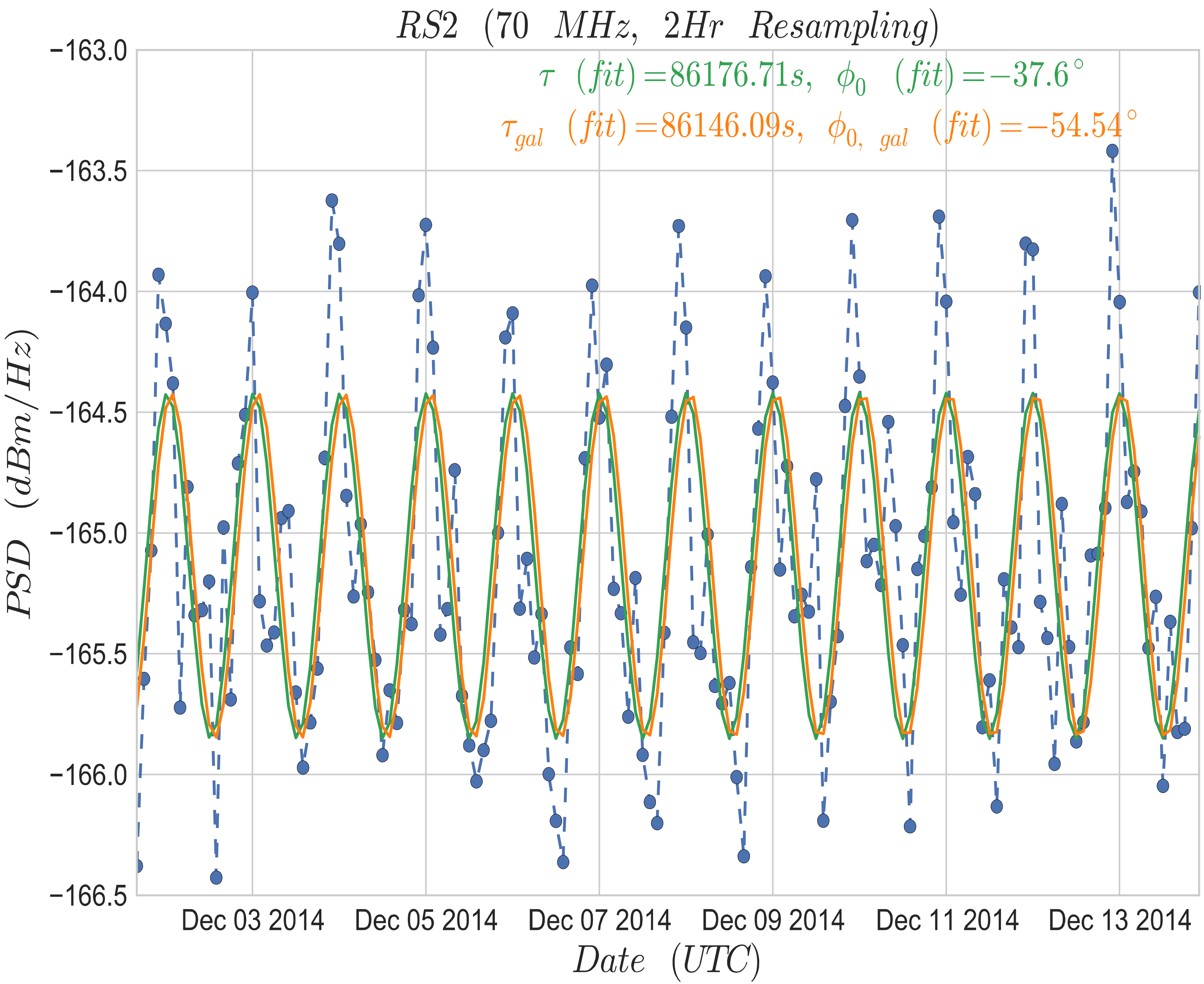
Forward *Gain* : *22.6 dBi*
Horizontal Beam Width : *12°*
Vertical Beam Width : *10°*

Chirps!



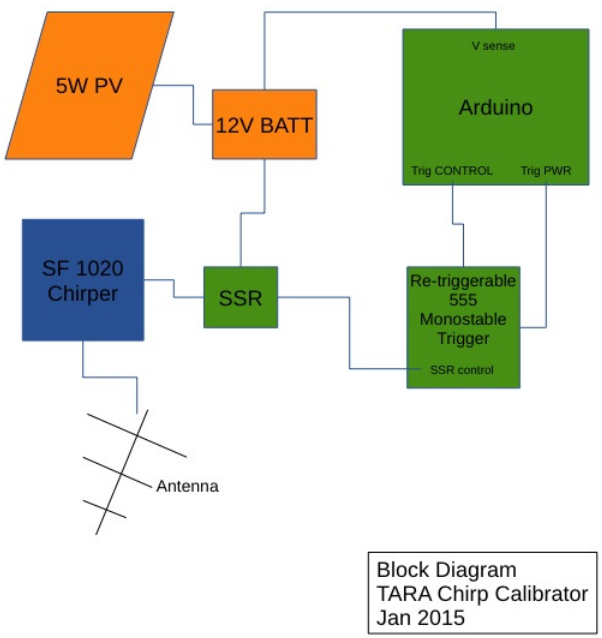
Frequency [MHz]
140
120
100
80
60
40
0
5
10
15
20
25
30
Time [μs]
PSD [dBm/Hz]
-150
-160
-170
-180
-190
-200
-210
-220
-230

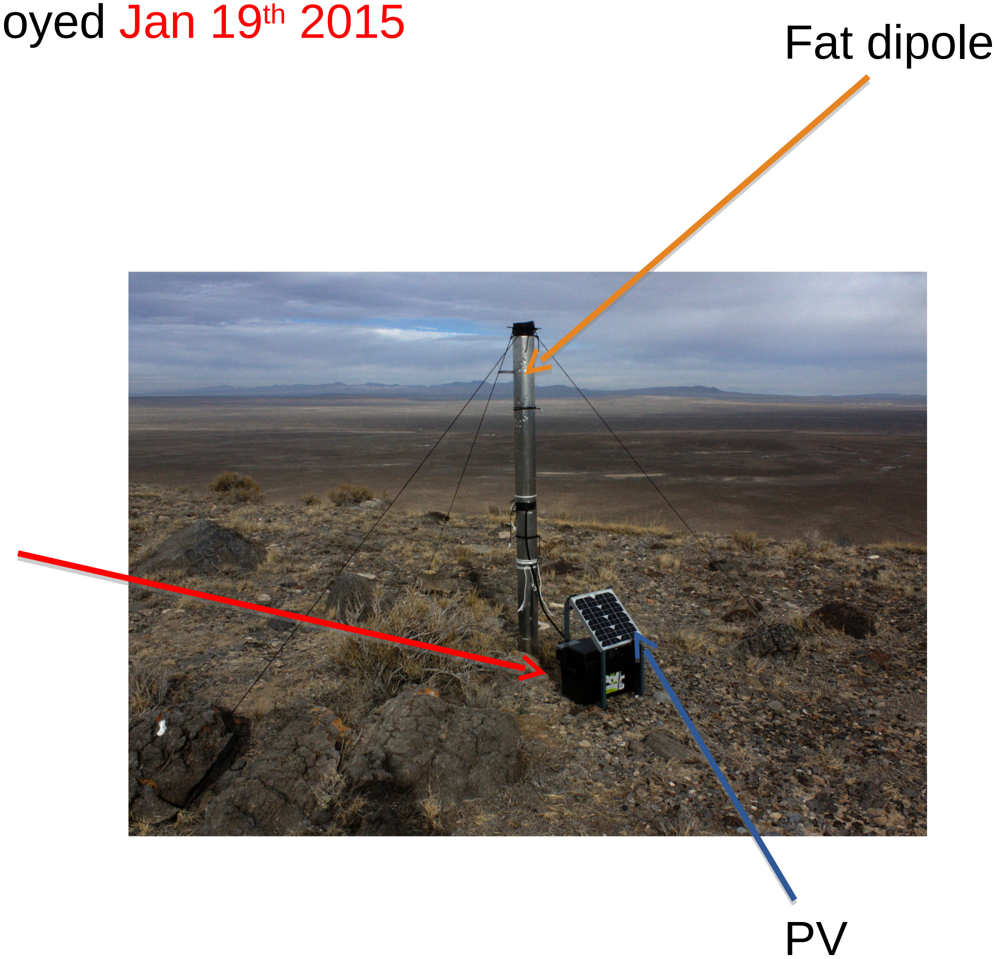
Sidereal Variation (wrt Sagittarius A*)



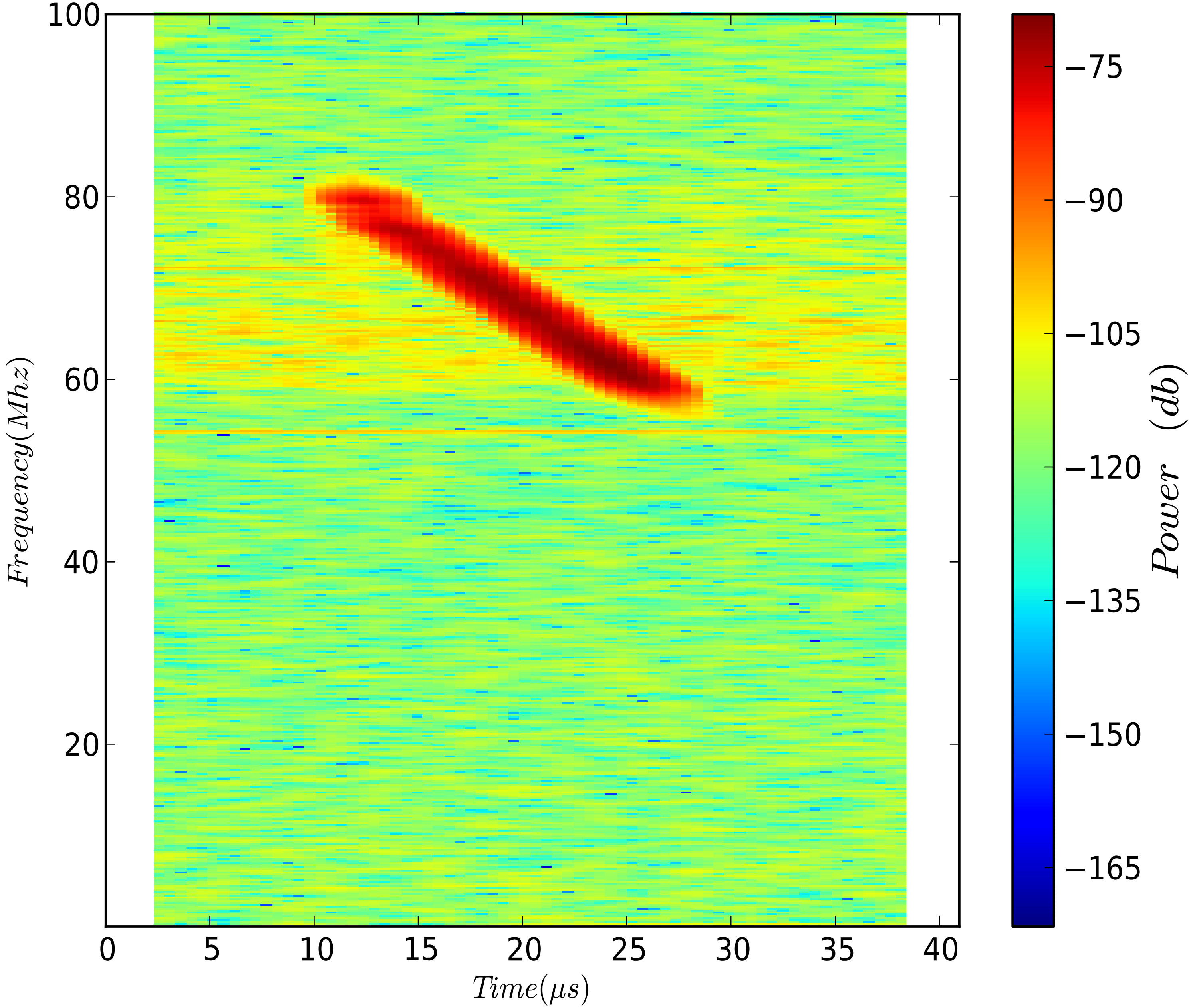
Chirp Calibration Unit (CCU)

Deployed Jan 19th 2015

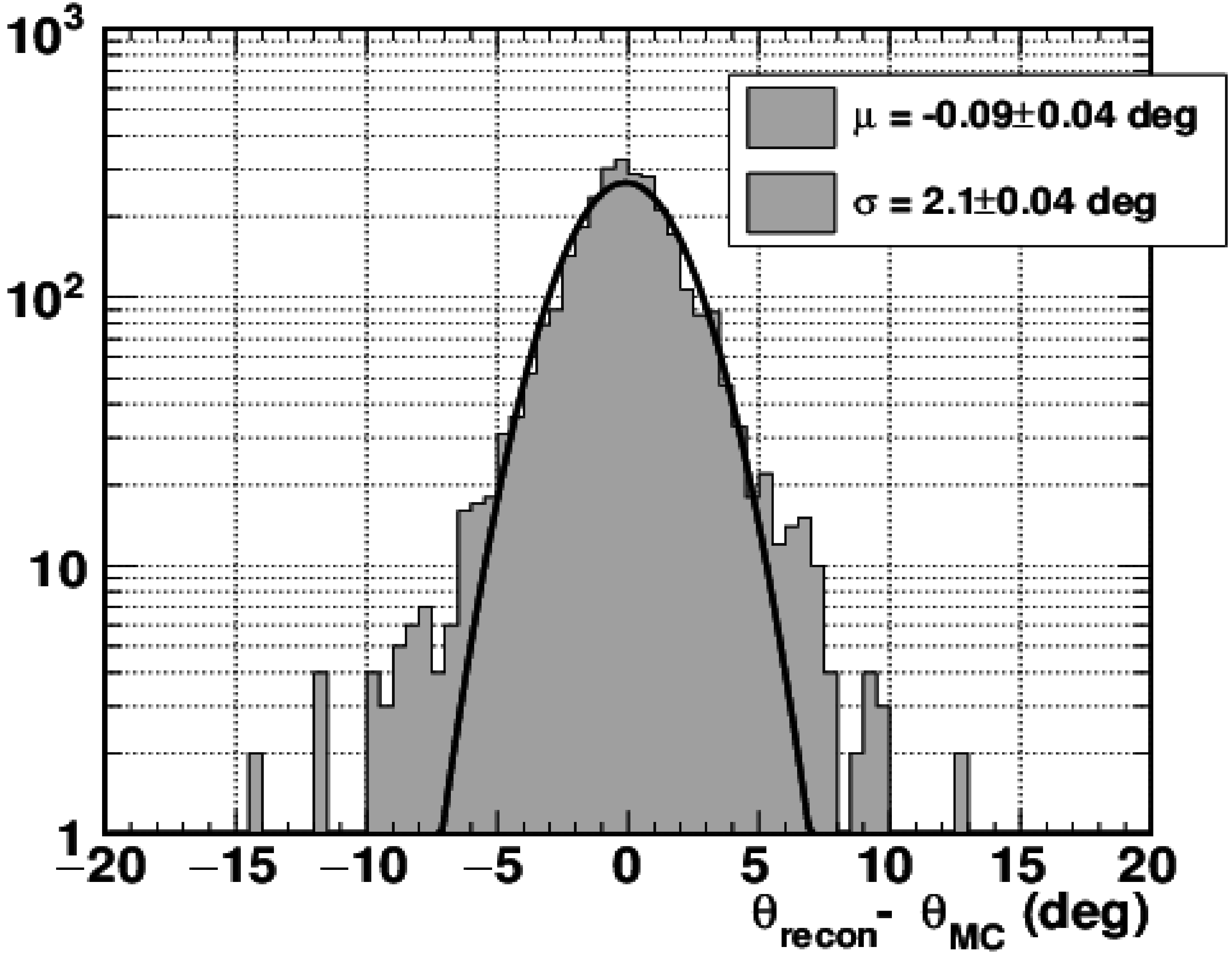




Field Calibration Chirp



Single antenna, dual-polarization zenith angle resolution (neural net, MC)



Next up (for me): India building on its current expertise and plugging into future CR detection experiments...