Radio Detection of High Energy Cosmic Ray Showers

Dr. Abaz Kryemadhi

Assistant Professor of Physics

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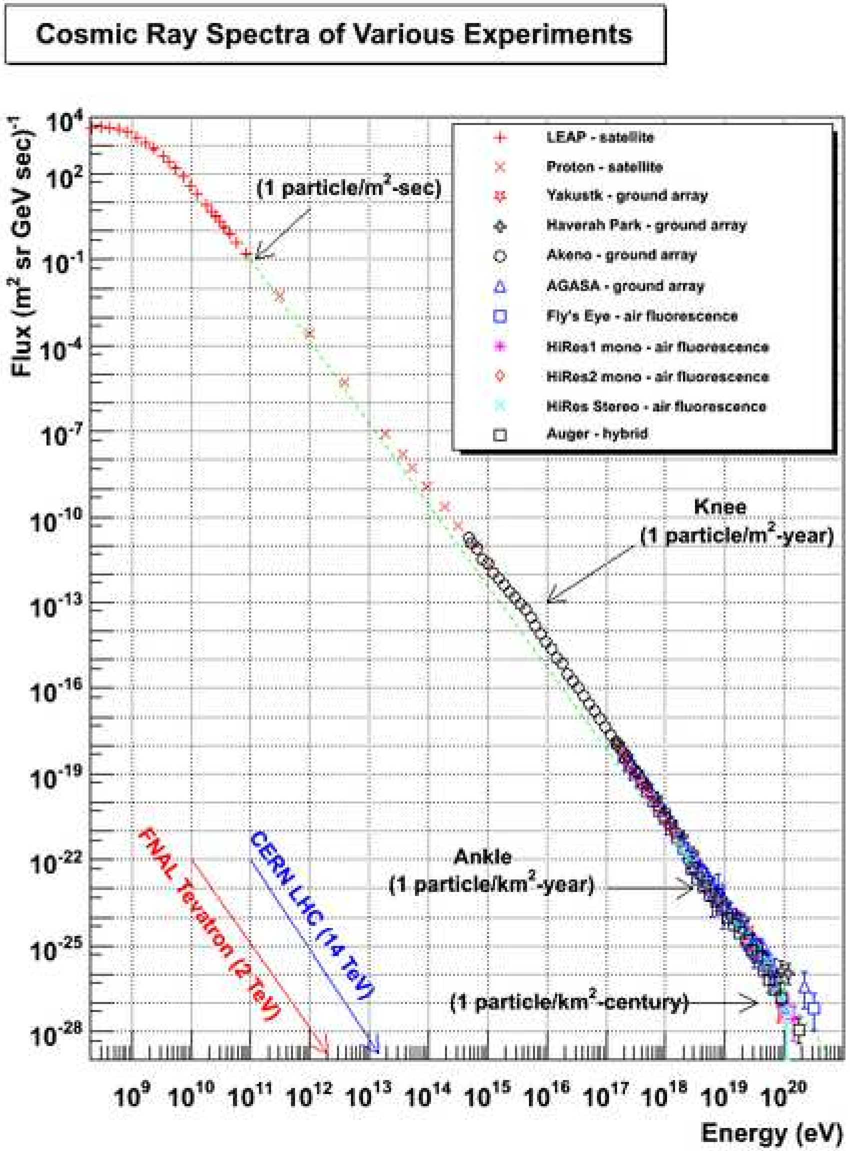
On Behalf of: Michael Bakunov, A. Maslov, A. Novoskoskya

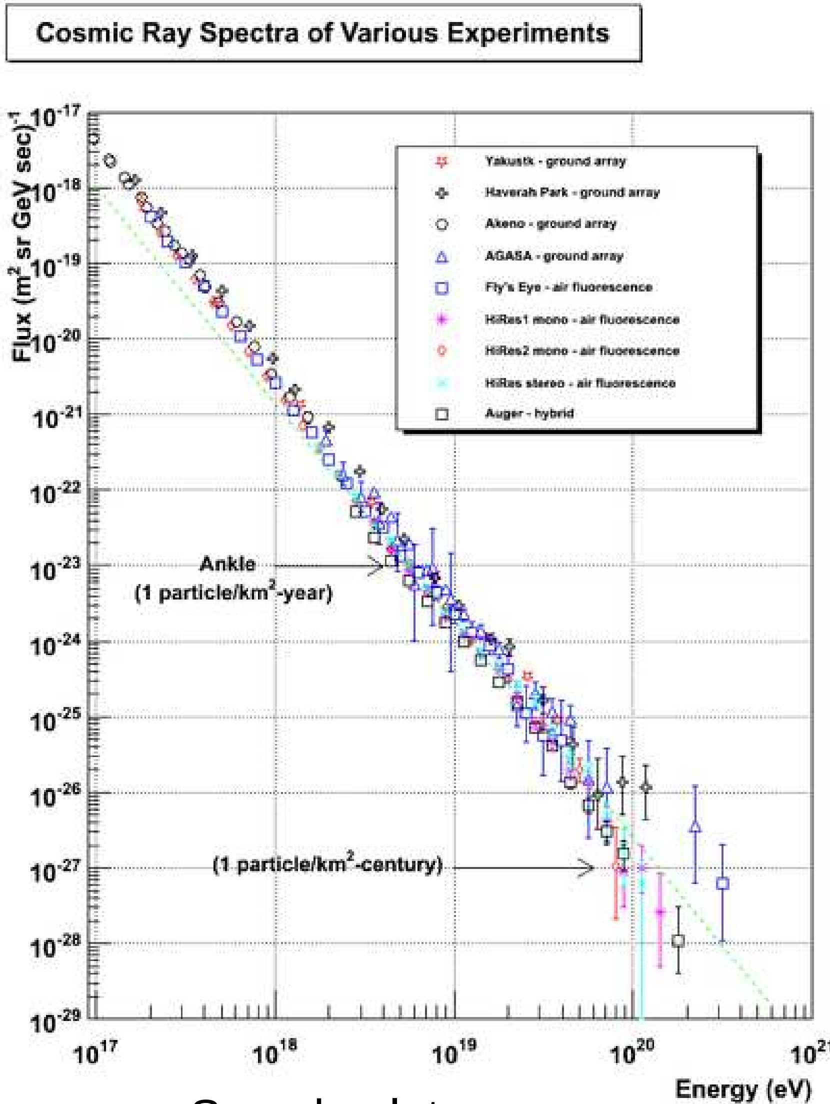
Also thanks to : Peter Gorham and Helio Takai, MARIACHI Collaboration

Outline

- Ultra High Energy Cosmic Rays (UHECR)s
  - Physics questions, extensive air showers, and detection technique
- Radar technique and motivation
- Detection of UHECRs via radio wave interaction with the relativistic moving ionization front
  - For incident frequency of 10 MHz
  - For medium wave frequencies, i.e 1 MHz
- Summary and Future prospect

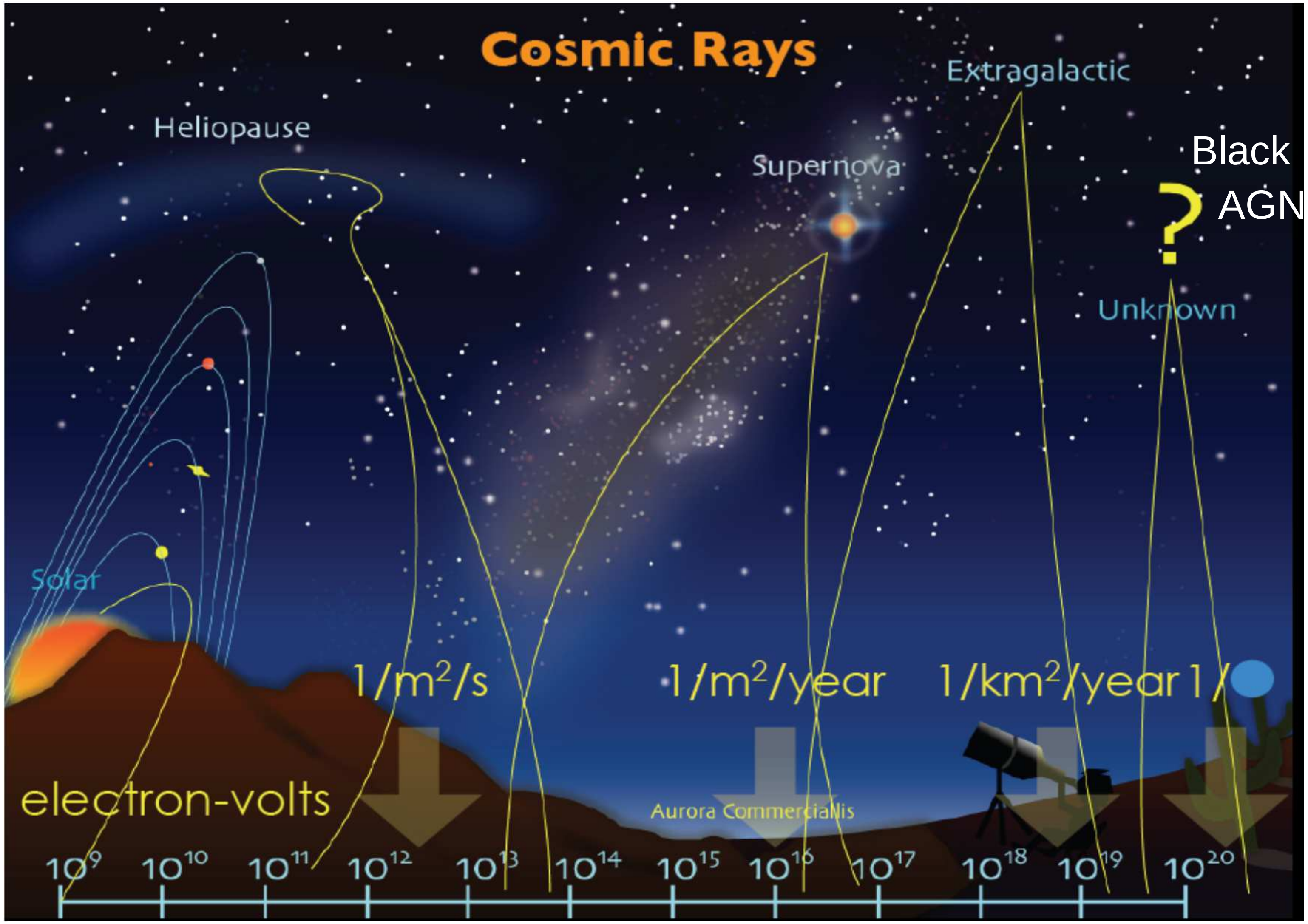
Energy spectrum of cosmic rays





Swordy plots

http://www.physics.utah.edu/~whanlon/spectrum.html

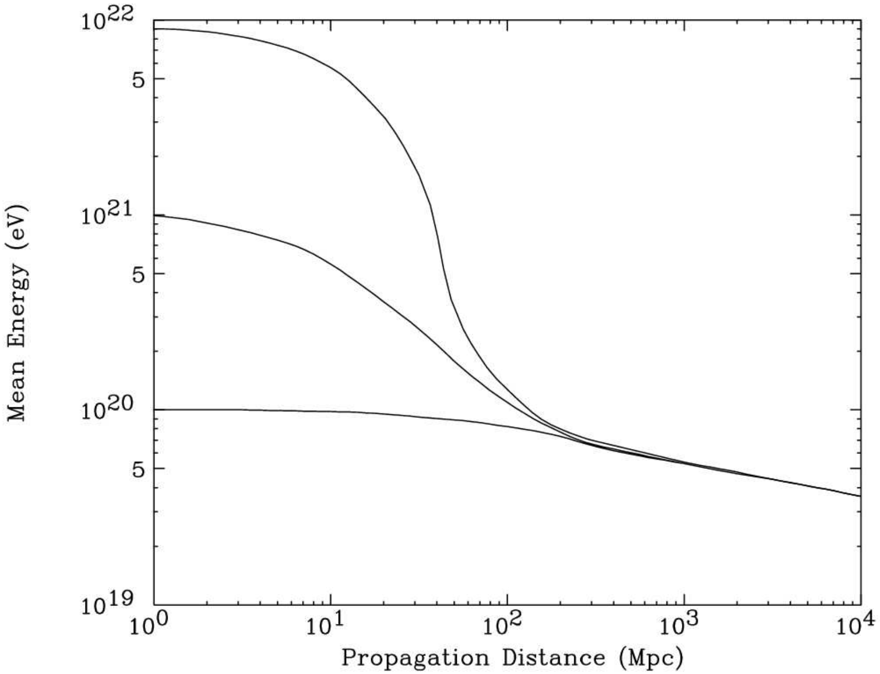


H. Takai

Physics Questions:

1. Where are they from?
2. How are the produced and accelerated?
3. Chemical Composition

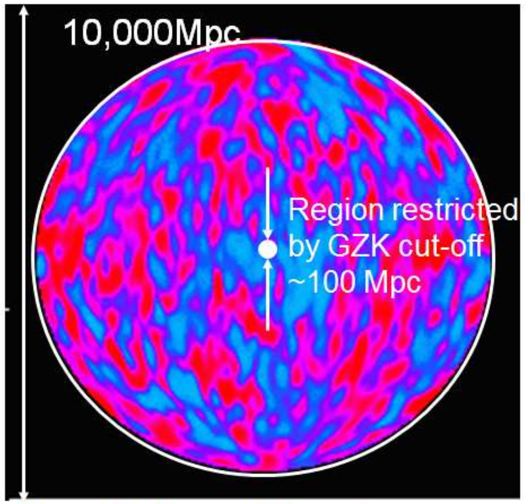
Greisen–Zatsepin–Kuzmin (GZK) Limit



Interaction of protons with Microwave Cosmic Background photons→

$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

$$\boxed{E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 4 \cdot 10^{19}\,\mathrm{eV}}$$



Size of observable universe

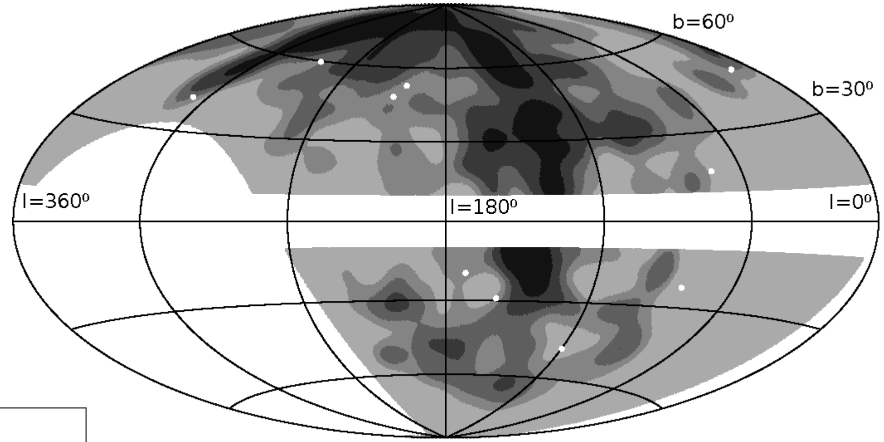
- Above ~ 4 x10^{19} eV, space becomes opaque to cosmic ray protons

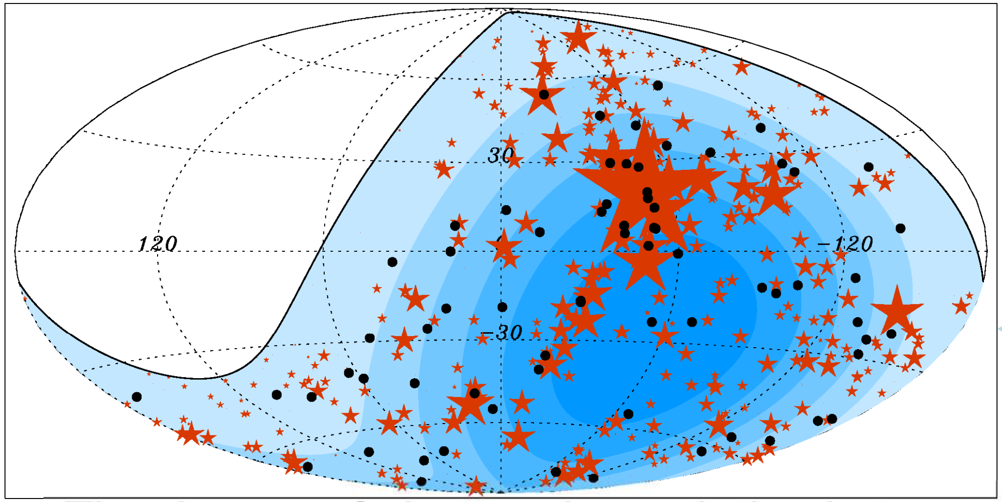
•Sources of CR with energies above the GZK limit must be 'close', < 100 Mpc

•No definite acceleration sites for such high energies established

Current Status of highest energy cosmic rays

HiRes result for particles with energy E>57 EeV, consistent with isotropic arrival direction; No correlation with known astrophysical sources within local universe

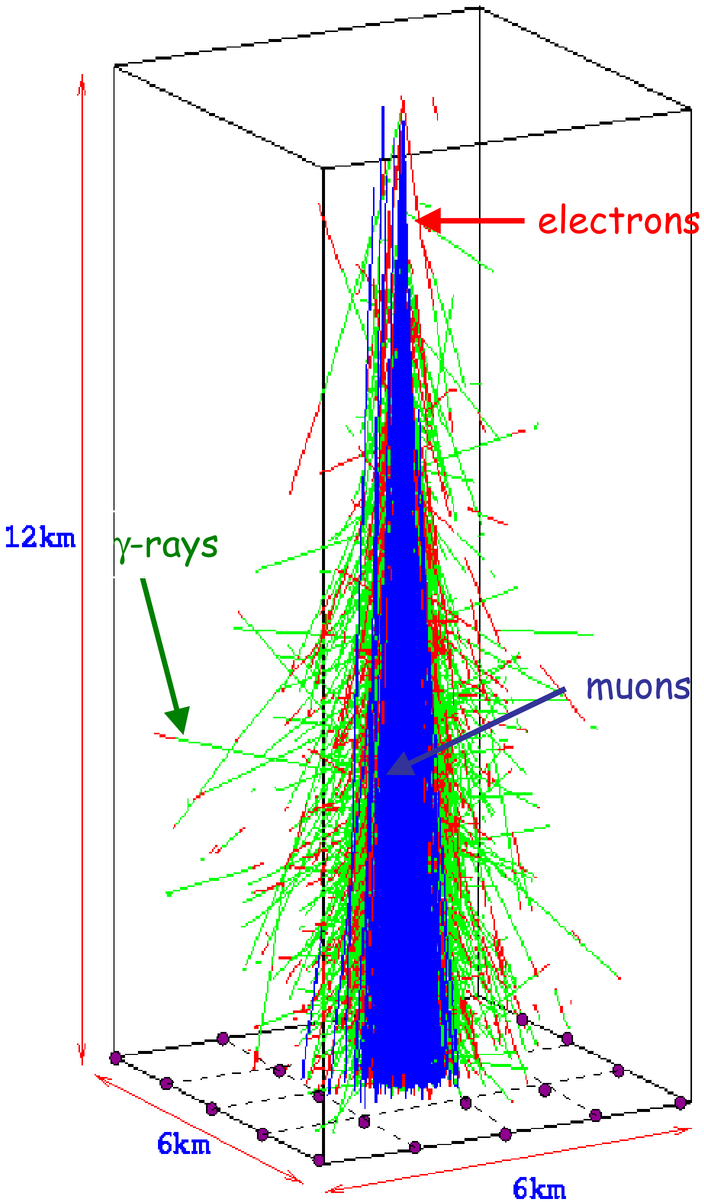


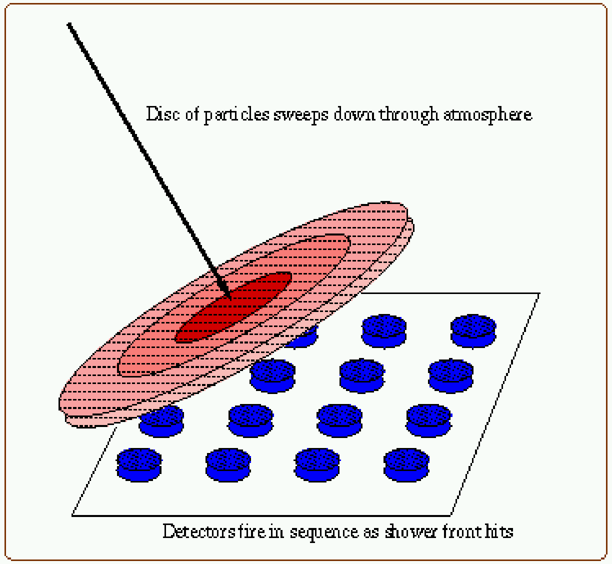


Auger data for cosmic rays with energy E>55 EeV

The degree of observed correlation between cosmic rays with active galaxies is $(38^{+8}_{-7})\%$ compared to 21% expected to occur by chance if the flux were isotropic. More statistics are needed in the GZK regime

Extensive Air Showers (EAS)





Number of electrons in the EAS in terms of primary particle energy E, and shower age s is:

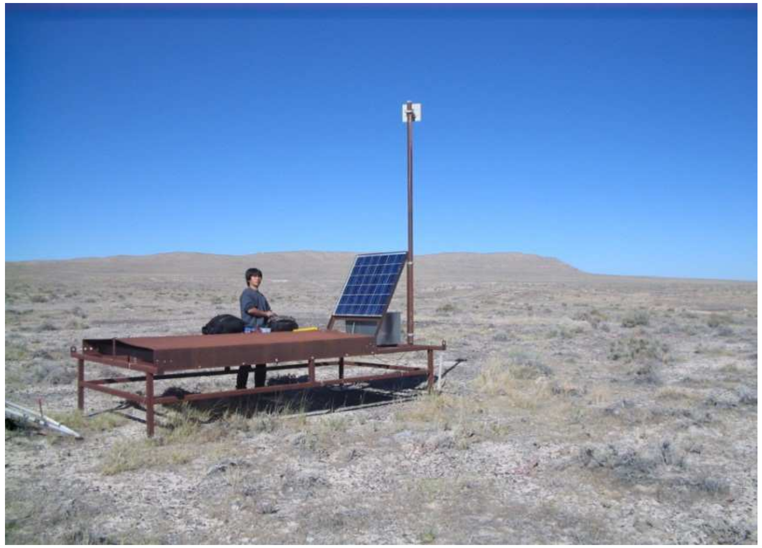
$$N_e = \frac{0.31 \exp[(d/X_0)(1 - 1.5 \ln s)]}{\sqrt{\ln(E/E_{crit})}}$$

The lateral spread of EAS, where r_m is the Moliere radius (r_m ~ 70 meters at sea level)

$$\xi_e = K_N \left(\frac{r}{r_m s_m}\right)^{s-2} \left(1 + \frac{r}{r_m s_m}\right)^{s-4.5}$$

Traditional Detection techniques: Ground Arrays

Water Cerenkov



Scintillator Counters

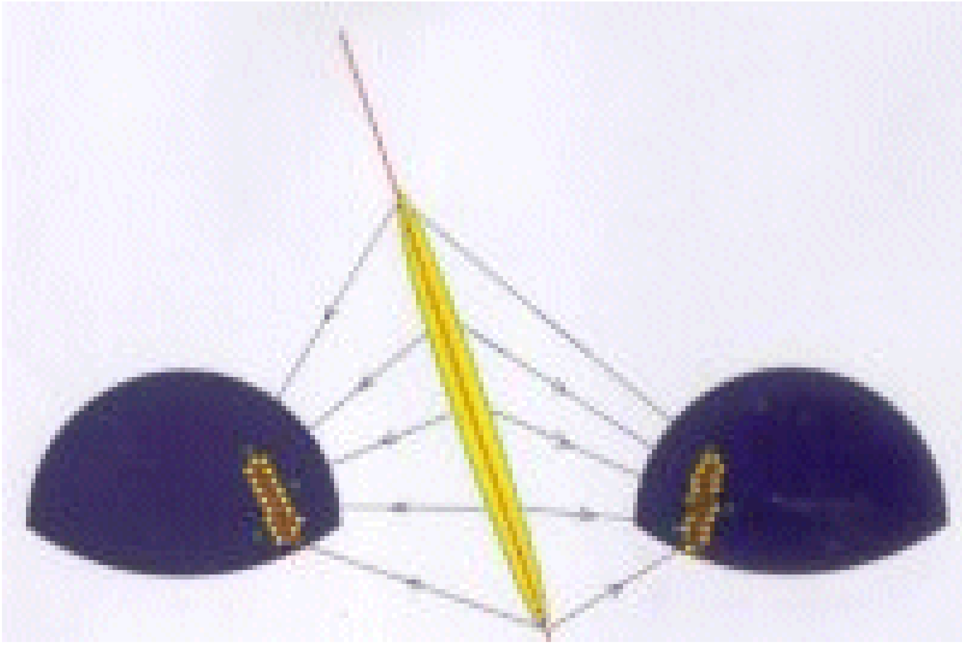
Pros:

- Well developed and understood

Cons:

- Only a slice of the shower is analyzed
- Need numerous stations for good statistics
- Expensive

Traditional Detection Techniques: Air Fluorescence



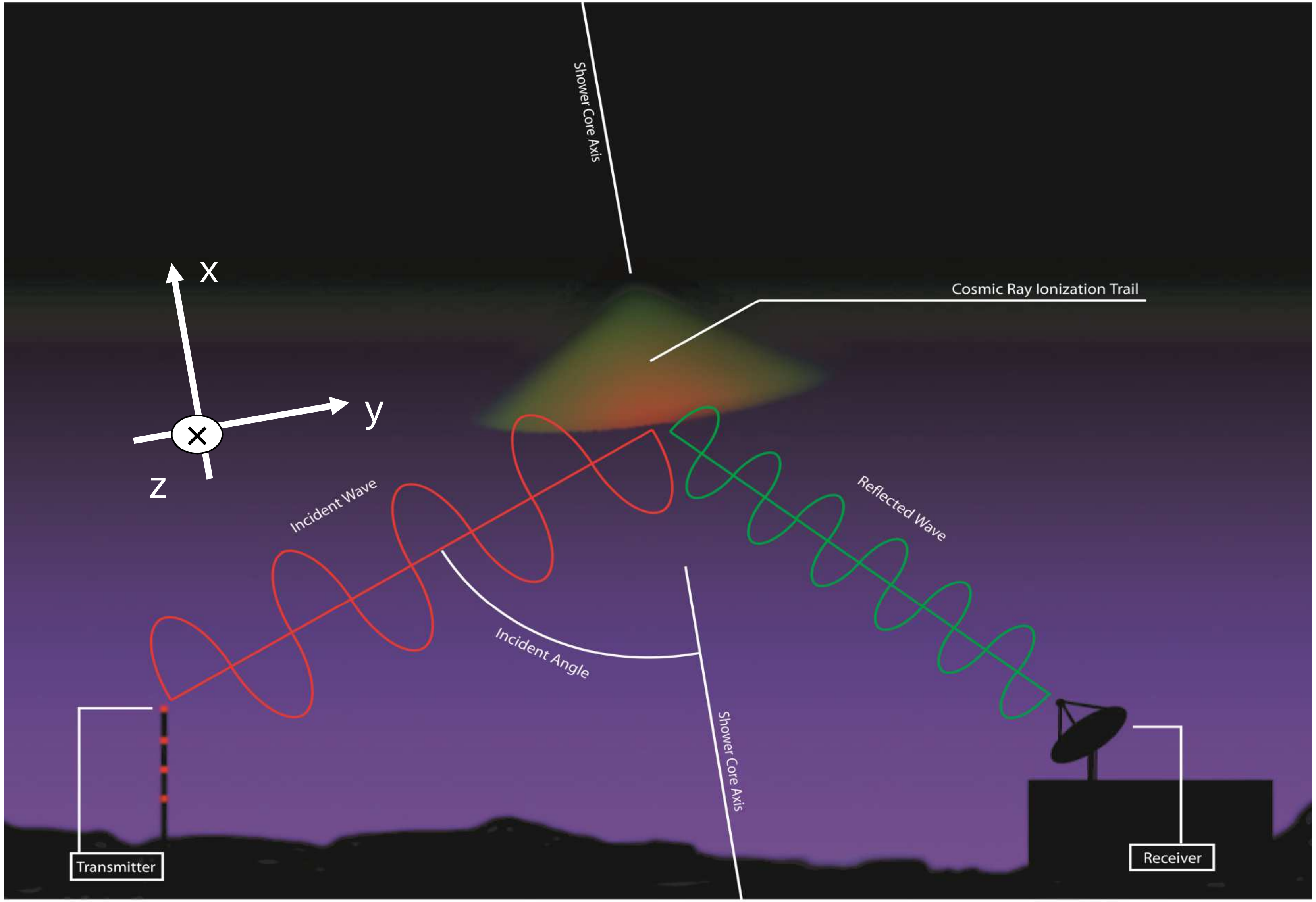
Cosmic ray showers produce ionization and excitation of gas molecules. Some of this excitation energy is emitted as visible and UV light.

Pros: Longitudinal image of the shower
Cons: Weather monitoring very critical
About 10% duty cycle (requires clear and moonless night)

Motivation for radio detection

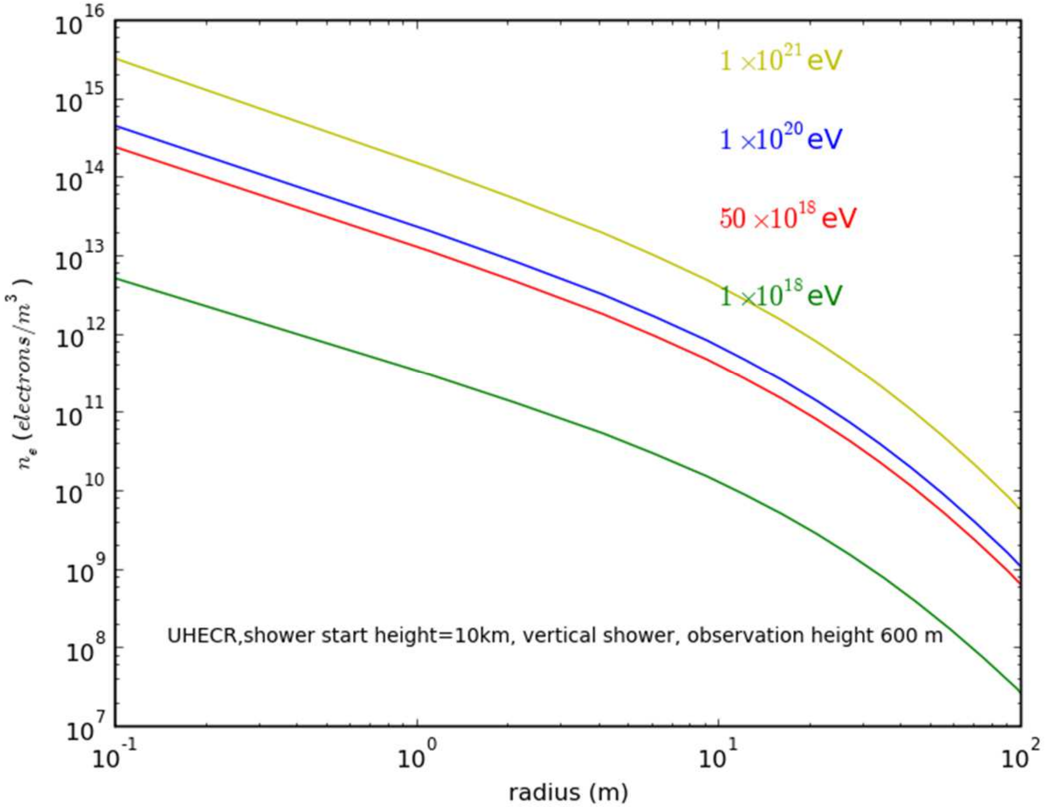
- Flux of high energy cosmic rays (>10^{18} eV) is very small
  - Radar detection may provide an alternative to current detection techniques with high duty cycle and longitudinal imaging of the showers.
  - Imaging of the shower is important since Monte Carlo QCD simulations do not have the input of particle physics accelerators at these energies, making it hard to control the systematic errors.
- Radar detection (will use "radar" and "radio" interchangeably)
  - The concept of radar-based detection for cosmic rays was initially proposed in 1940 (Blackett & Lovell) but with no experimental results so far.
  - Previous models assumed long cylindrical ionization fronts, and reflection was expected in the same frequency range as incident frequency.
  - The ionization front is more disk-like due to short plasma lifetime and moves with relativistic speed.
    - Fast moving front produces frequency up-shifts due to Doppler Effect.
    - This partially explains the lack of experimental results.
  - **In our model we properly account for the relativistic effect**

Concept of Radar Detection



Ionization & Plasma Lifetime for UHECR

Shower electron energy goes mostly into ionization with a yield of about 1 ion pair per 33 eV energy.



Plasma lifetimes for the typical UHECRs altitudes are 10-100 ns

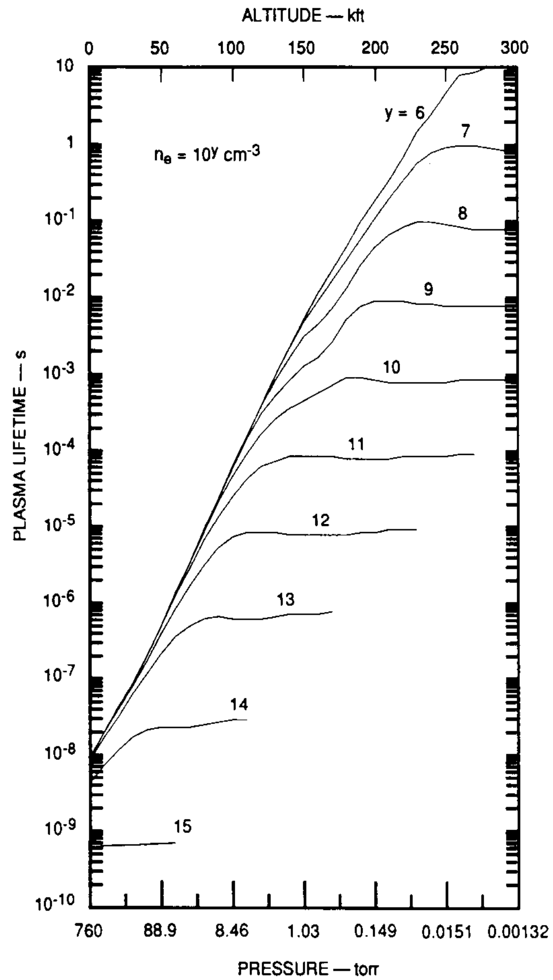
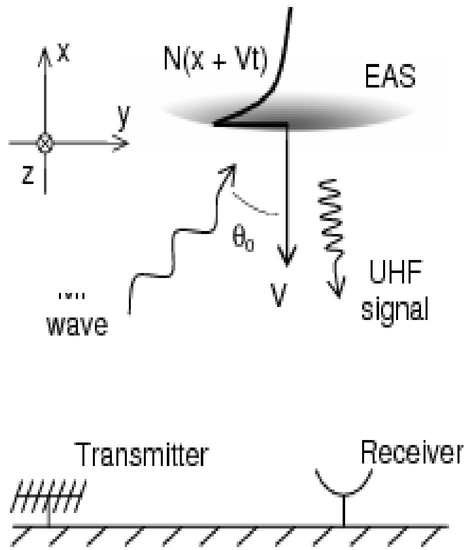


Fig. 2. Plasma lifetime of air versus altitude.

R. J. Vidmar

Reflection of Electromagnetic (EM) Waves from a moving ionization front

- An EM wave with frequency ω_0 incident on a moving ionization front with velocity *V*<*c*, the ionization front is produced by the extensive air showers (EAS) of high energy cosmic rays.
  - The radial extent of the ionization front is ~Moliere radius
- The front creates an immovable plasma of density N_0 that decays in time with rate μ
- With $\Theta(x+Vt)$ as a heavy side step function, the plasma density profile is:



$$\boxed{N(x+Vt) = N_0 e^{-\frac{\mu}{V}(x+Vt)}\Theta(x+Vt)}$$

- Assume a TE polarized incident wave

Reflected frequency

Phase continuity at the front ($x = -Vt$) yields

$$f_r = \frac{\omega_r}{\omega_0} = \gamma^2 (1 + 2\beta n \cos(\theta_0) + \beta^2 n^2)$$

$\gamma = (1 - \beta^2 n^2)^{-1/2}$ is the Lorentz factor

$\beta = V / c$

n is refractive index of air

θ_0 is the incident angle

Maxwell's equation

To find reflection coefficient
use Maxwell's equations and
the current density equation for free
electrons in a time varying plasma

$$ih_0 E_z = \frac{1}{c}\frac{\partial B_x}{\partial t},$$

$$\frac{\partial E_z}{\partial x} = \frac{1}{c}\frac{\partial B_y}{\partial t},$$

$$\frac{\partial B_y}{\partial x} + ih_0 B_x = \frac{n^2}{c}\frac{\partial E_z}{\partial t} + \frac{4\pi}{c} j_z$$

$$\frac{\partial j_z}{\partial t} = \frac{e^2 N}{m} E_z - (\nu + \mu) j_z,$$

where ν is the electron-neutral collision frequency

Definitions

$$\omega_p = \sqrt{\frac{4\pi e^2 N_0}{mn^2}}$$

Plasma frequency which remains invariant under transformation

$$f_p = \frac{\omega_p}{\omega_0}$$

Plasma frequency relative to incident frequency

$$f_t = \frac{\omega_t}{\omega_0}$$

Transmitted frequency relative to incident frequency: the solution yield two transmitted frequencies

$$f_\nu = \frac{\nu}{\omega_0}$$

Collision frequency in the plasma relative to incident frequency

Reflection Coefficient

The continuity of Electric and magnetic field and their derivatives across the front yield for the reflection coefficient R:

$$\boxed{R = \frac{E_r}{E_0} = -f_r \frac{(f_{t1}-1)(f_{t2}-1)}{(f_{t1}-f_r)(f_{t2}-f_r)}}$$

Where in the limit of strong collisions (f_ν >>1, f_ν >>f_p^2) and highly relativistic γ>>1, the physically meaningful transmitted wave frequencies f_{t1} and f_{t2} are:

$$\boxed{f_{t1} = 1 + i\tilde{f}_p^2 f_\nu^{-1}}$$

→ This wave propagates practically in the incidence direction

$$\boxed{f_{t2} = if_\nu + \frac{\tilde{f}_p^2}{1 + f_\nu^2[2\gamma^2(1+\cos\theta_0)]^{-2}}}$$

→ This wave decays very fast

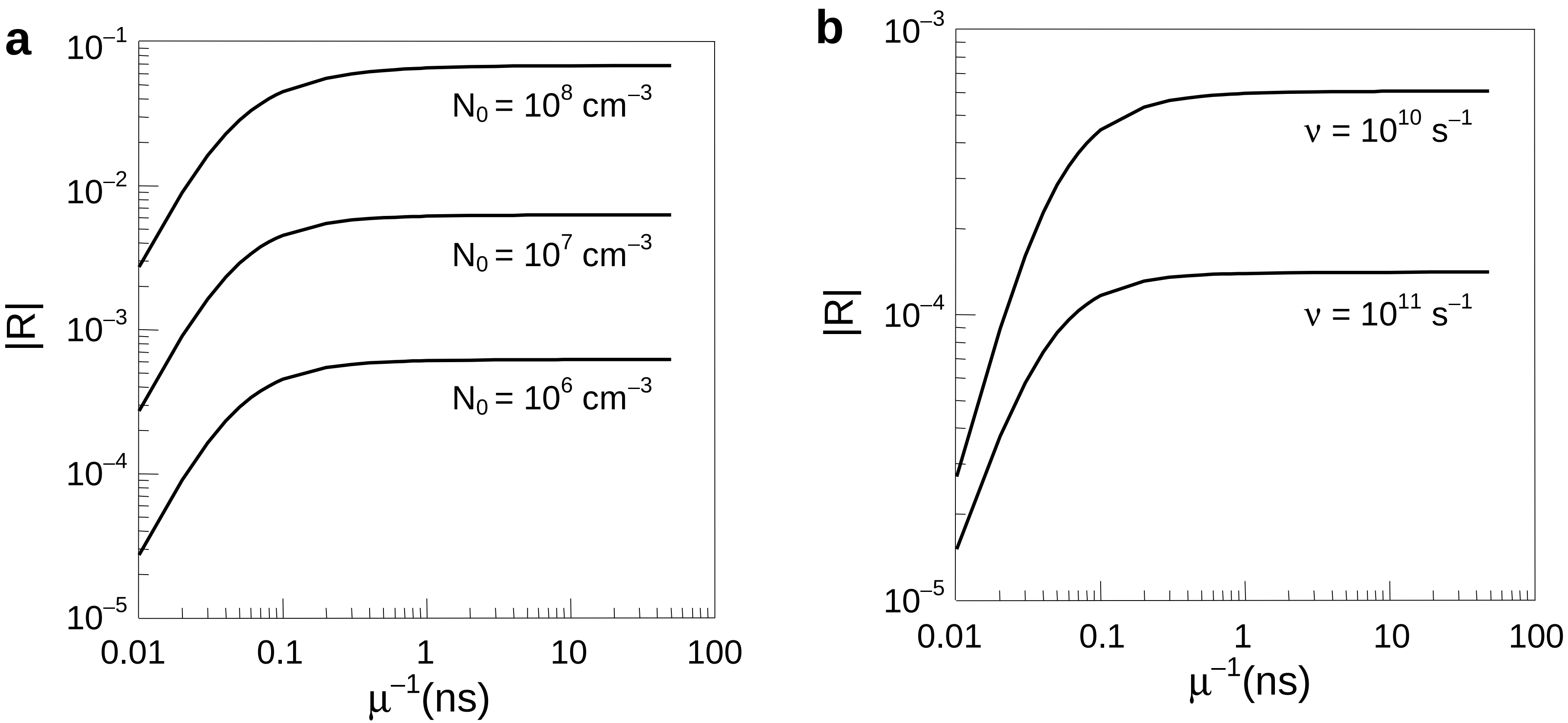
Where $\tilde{f}_p$

$$\boxed{\tilde{f}_p^2 = f_p^2[2(1+cos\theta_0)]^{-1}}$$

Results for 10 MHz incident wave

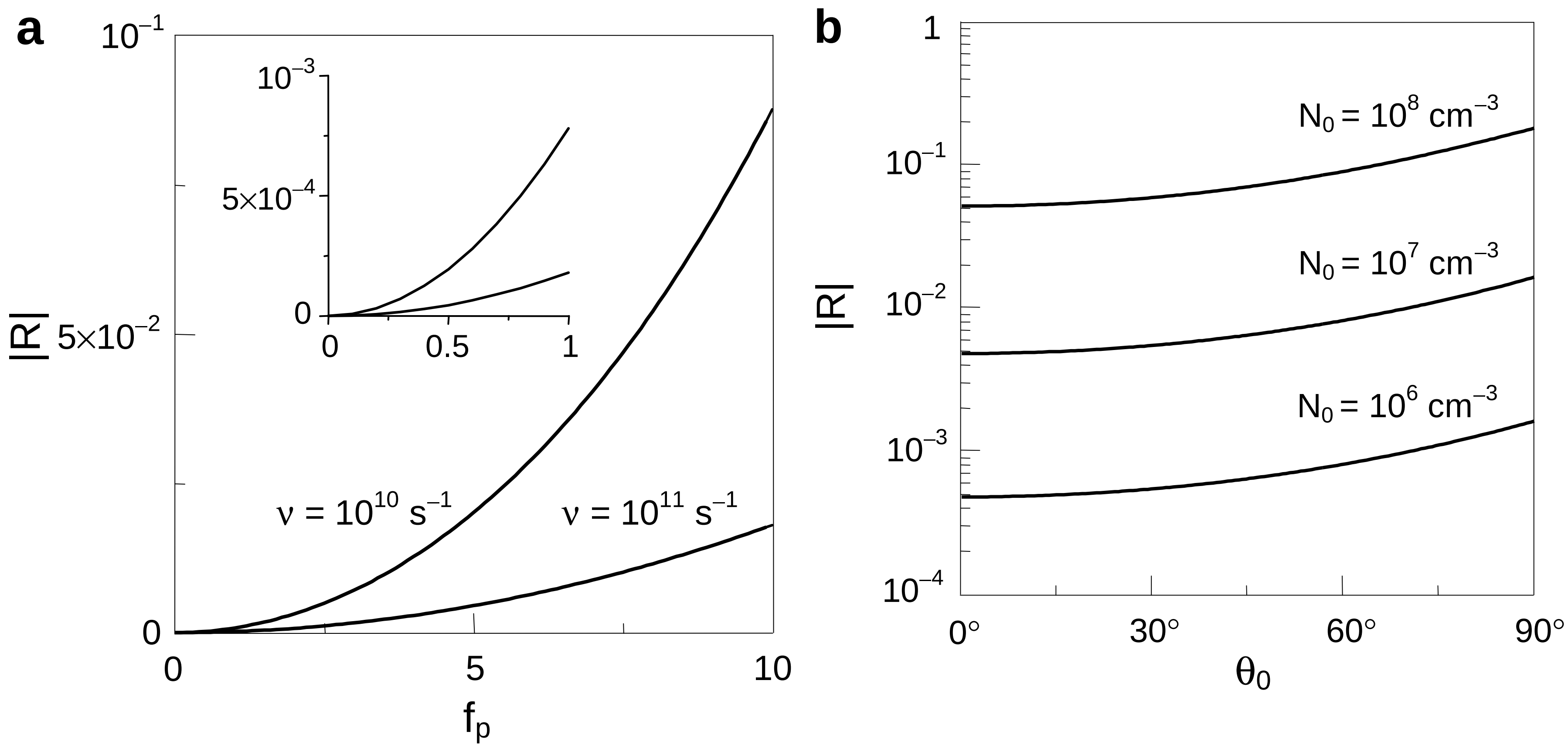
- For a 10 MHz incident wave (wavelength <size of the ionization disk 30 m<~200 m)
  - Plane boundary approximation therefore was used, modeling was easier
  - It was a good starting point to see the feasibility of the technique
  - Results already published:
  - *M. I. Bakunov, A. V. Maslov , A. L. Novokovskaya , A. Kryemadhi Astropart. Phys. 33 (2010) 335*
- *The following results represent the work from this paper*

Reflection Coefficient for Different Plasma Lifetimes

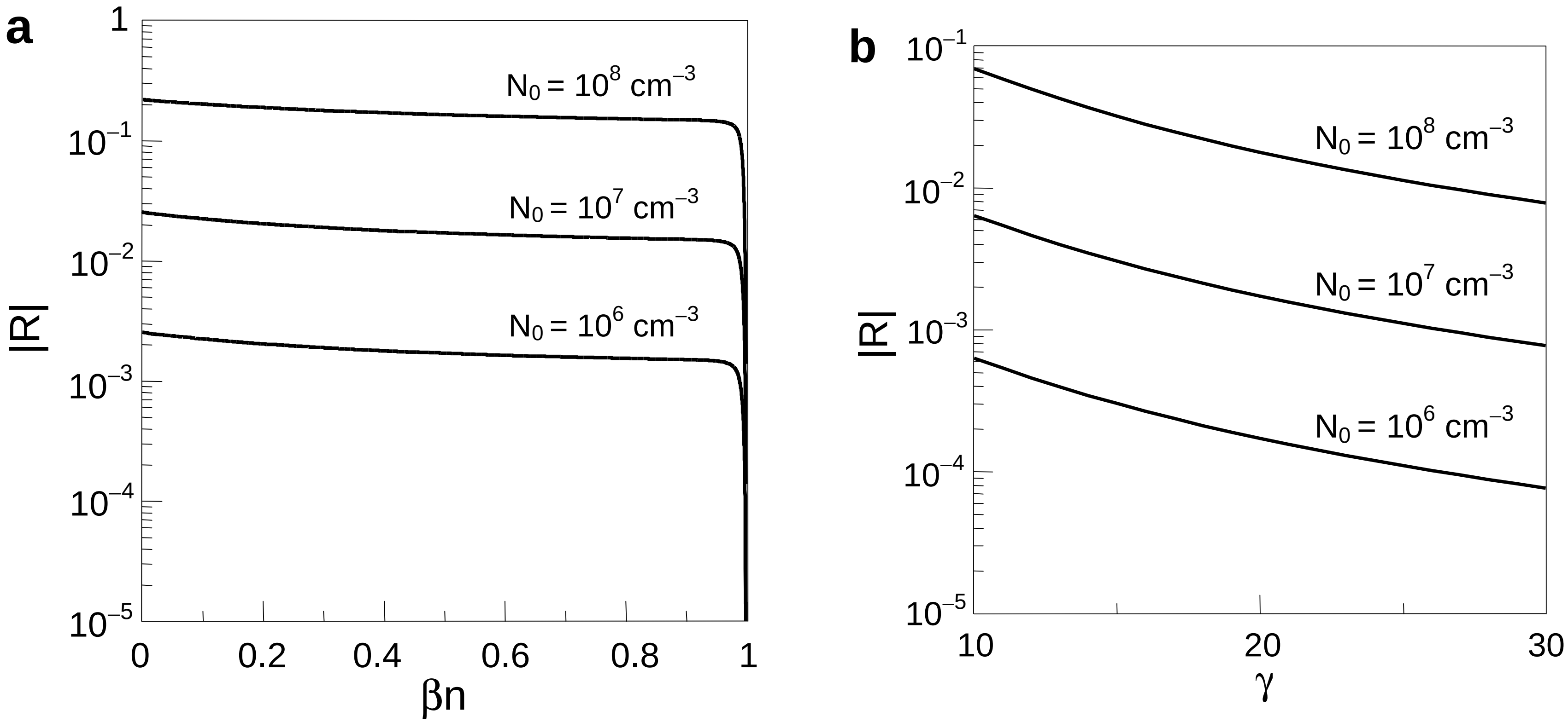


For EAS altitudes plasma lifetimes are in the range 10-100 ns. Small plasma lifetime does not appreciably affect the reflection coefficient.

Reflection Coefficient for Different Plasma Frequencies and Angles



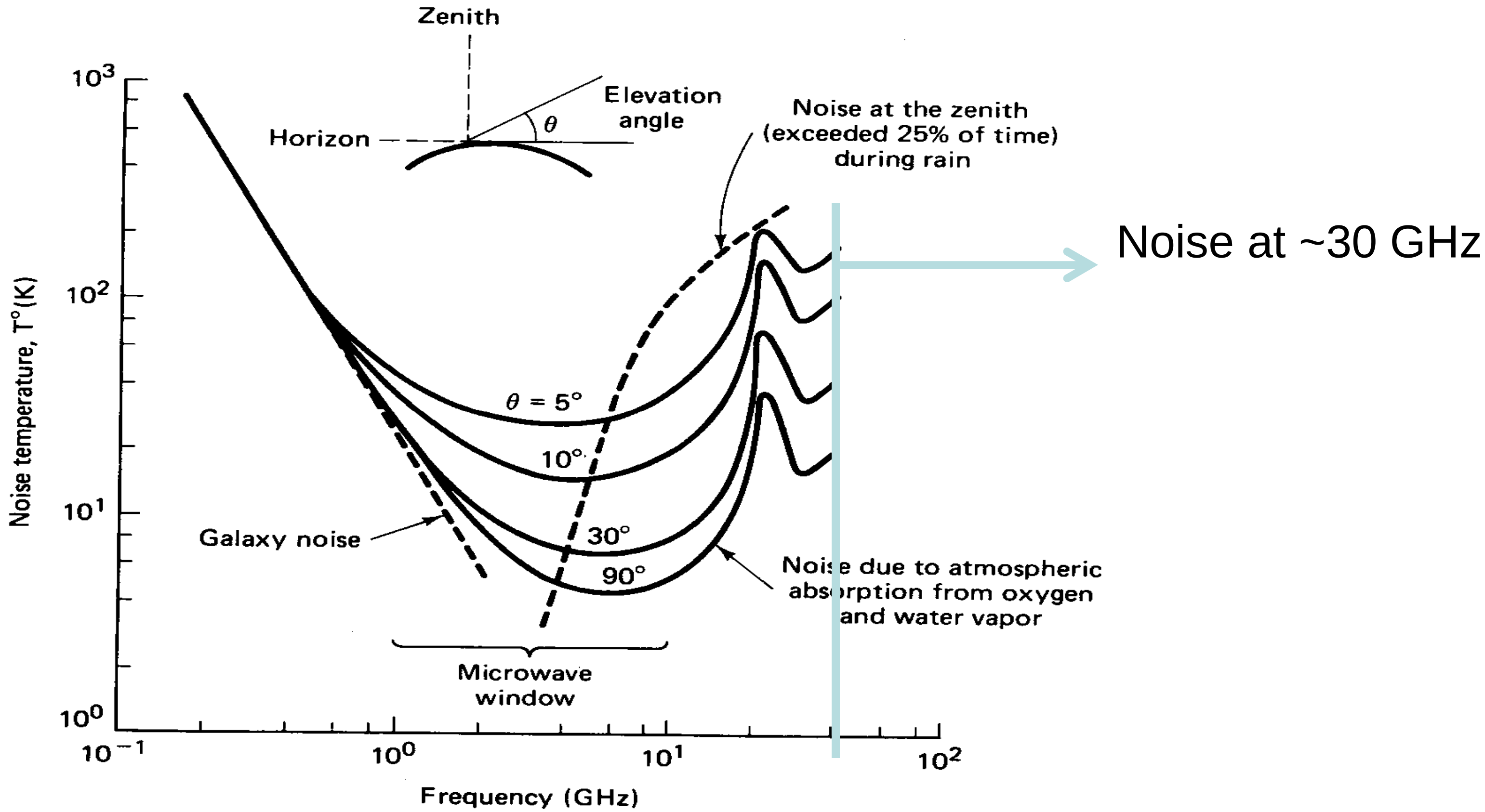
Reflection Coefficient for Different Front Velocities



Prospect for Detection (Returned Power)

- Power of the returned signal $P_r = P_e |R|^2 A / 2\pi r^2$
  - For typical (EAS) altitudes and EAS lateral extents, one can neglect the diffractive spread of reflected beam.
    - Reflection is beamed close to shower axis.
  - P_e is the power from transmitter (we assume $P_e = 200$ kW)
  - R is the reflection coefficient $\sim 0.77 \times 10^{-3}$ for
    - Plasma density $N_0 = 10^7 \text{cm}^{-3}$, collision frequency $\nu = 10^{10}\ \text{s}^{-1}$, $\gamma = 30$, $\theta_0 = 45^0$, and incident frequency $\omega_0 / 2\pi = 10$ MHz
  - A is the effective area of the receiving antenna (we assume $A = 3\text{x}10^{-3}\ \text{m}^2$ for a typical antenna).
  - r is the distance from transmitter to ionization ($r \sim 10$ km).
  - Including the effect of the EAS curvature reduced the reflected power by 4.
  - The reflected power P_r is then: ~ 0.14pW ~ -98.5dBm and reflected frequency $\omega_r / 2\pi = 30.7$ GHz

Noise



Sklar, pg. 225

Prospect for Detection (Noise and Bandwidth)

- For the above frequencies, Sky Temperature is T_{sky}~30 ^{0}K, and assuming a receiver noise $T_{receiver}$~130 ^{0}K, the noise power per unit bandwidth is $p_N=k(T_{sky}+T_{receiver})\sim 2.2\times 10^{-21}$W/Hz
  - We set the condition for detection as $P_r=p_n\Delta\omega_r$, which yields $\Delta\omega_r=64$ MHz or $\Delta\omega_r/\omega_r=2\times 10^{-3}$
- The bandwidth of the signal is given by

$$\frac{\Delta\omega_r}{\omega_r}=\frac{\Delta\omega_0}{\omega_0}+\frac{\sin\theta_0\Delta\theta_0}{1+\cos\theta_0}+\frac{2\Delta\gamma}{\gamma}$$

  - The first term can be very small, for instance an AM broadcast transmitter ($\Delta\omega_0$ /2π=2kHz, $\Delta\omega_0/\omega_0=2\times 10^{-4}$).
  - The second term can be made small by choosing small illumination angles (less then 10^{0}).
  - Third term is difficult to estimate since there is no directly calculated Lorentz factor for the showers and its variation as shower ages.

Other Considerations & Summary for 10 MHz incident wave

- One effect that could prevent detection is shortening of the reflected wave packet by the finite propagation of the front:

  - The duration of a wave packet passing a distance Δh is

    $\tau_r=(1-\beta n)\Delta h/V \sim \Delta h/2c\gamma^2$,

    for $\Delta h=1$ km, $\gamma=30$, $\tau_r\sim 2$ ns,

    and corresponding bandwidth ~500 MHz

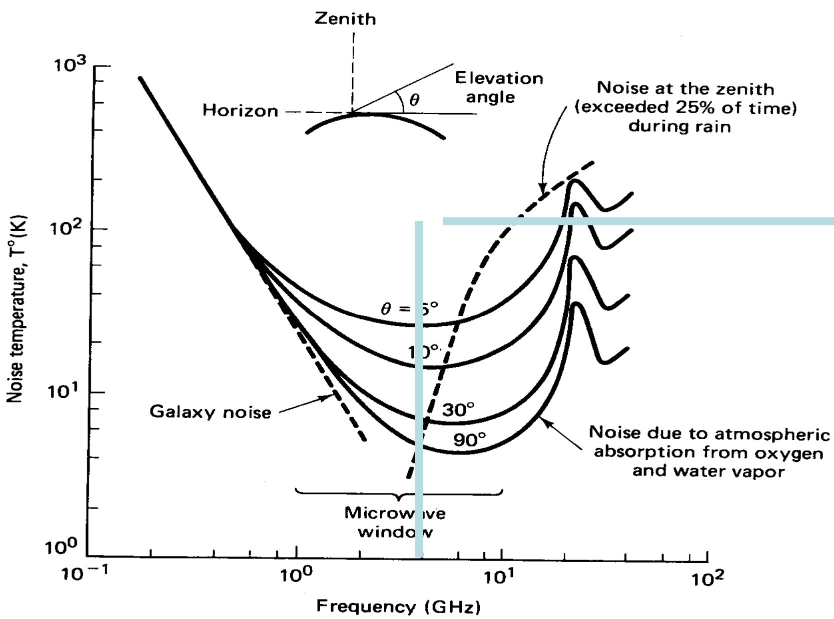
- Radar detection of high energy cosmic rays may be possible with modern radio receivers.

- The modeling developed properly accounts for relativistic blue shift.

- To detect EAS in this case one has to either increase transmitter power or use directed radiation pattern.

Prospect for detection of high energy cosmic rays using Medium frequency Waves (300 kHz -1 MHz)

- Using MF waves was motivated by the fact that the reflection coefficient presented for 10 MHz incident waves, if extrapolated to this frequencies would increase.
- The frequency of the reflected signal would decrease (for instance for 1 MHz incident frequency, the reflected frequency would be ~3 GHz).
- Sky noise at this frequencies is much smaller than at 30 GHz.

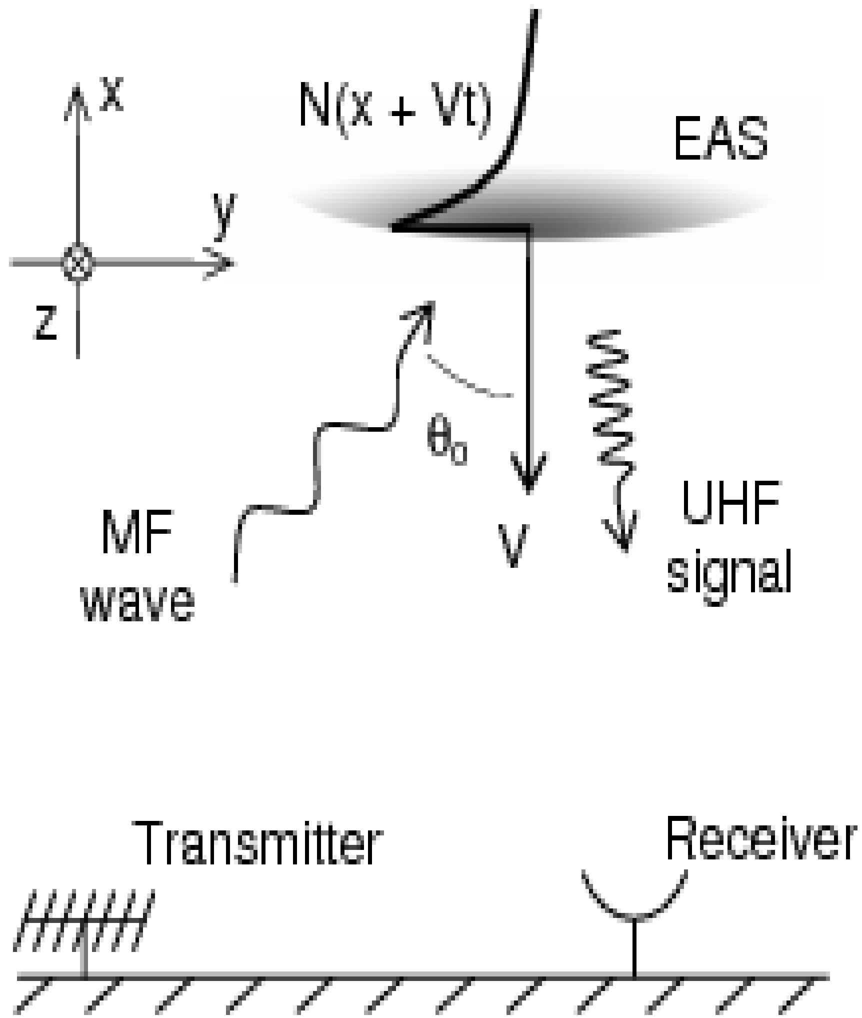


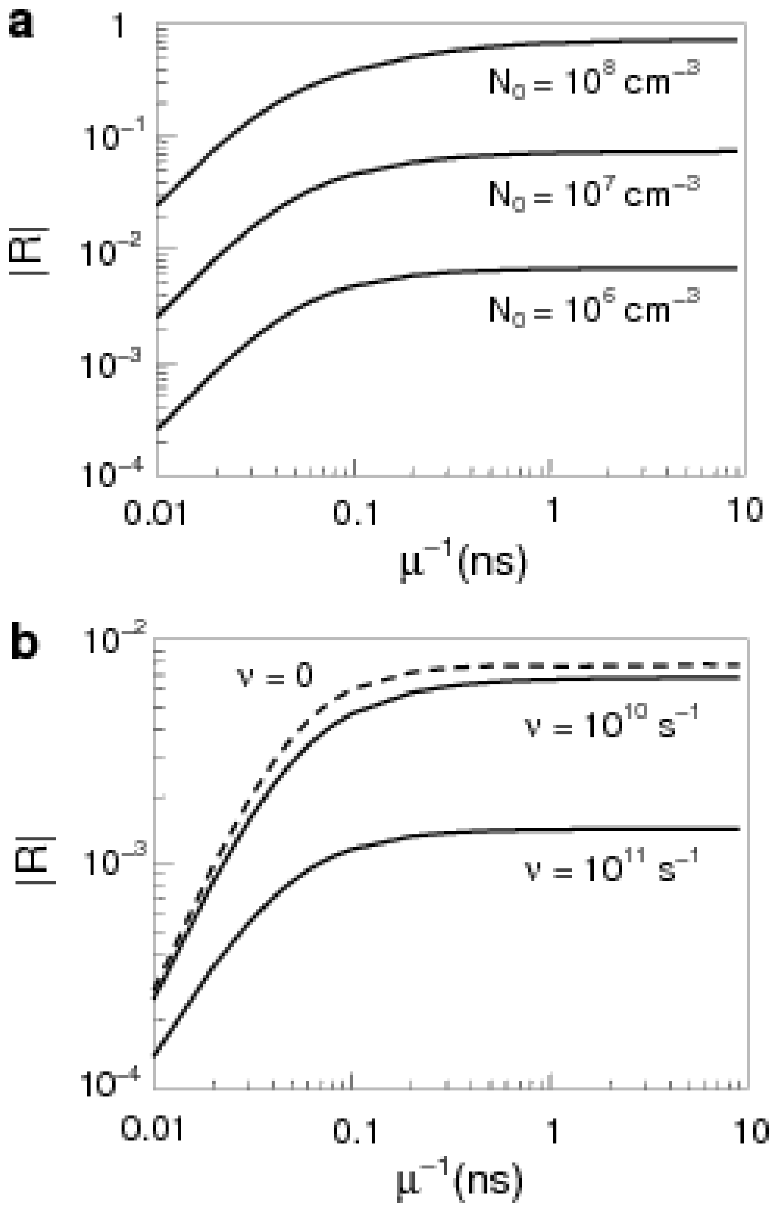
Sweet spot between the atmospheric noise and galactic noise

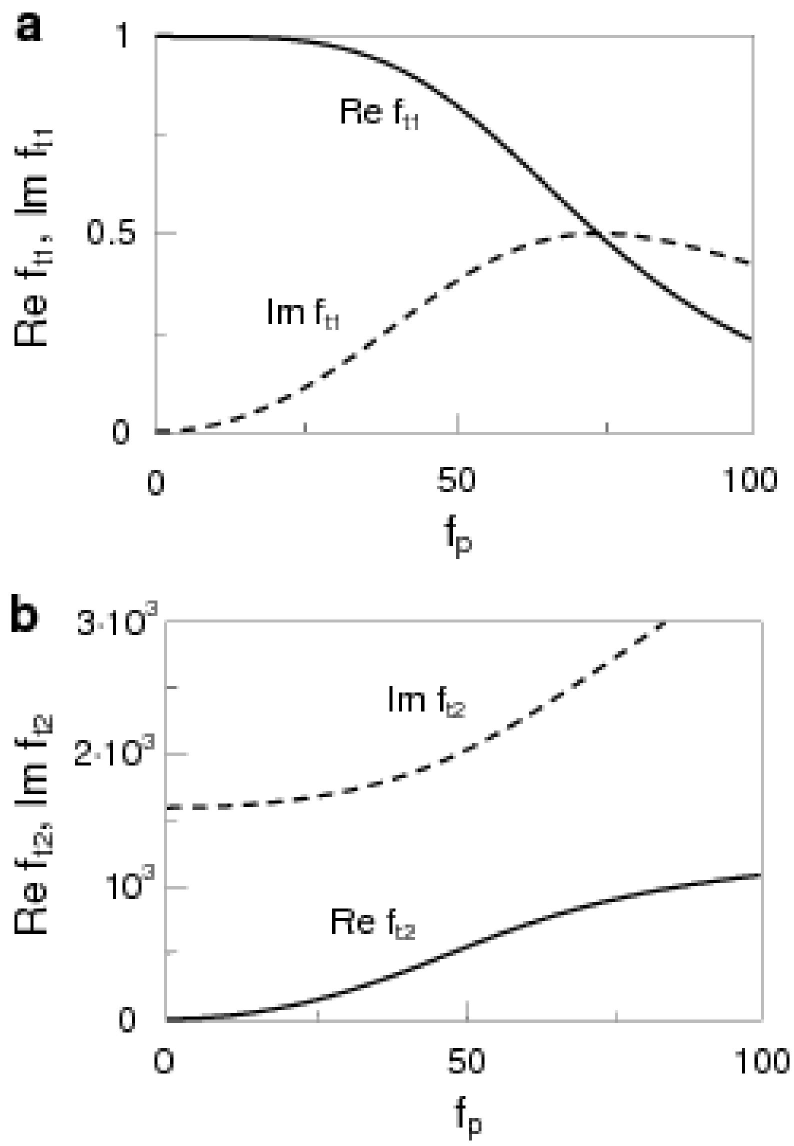
Sklar, pg. 225

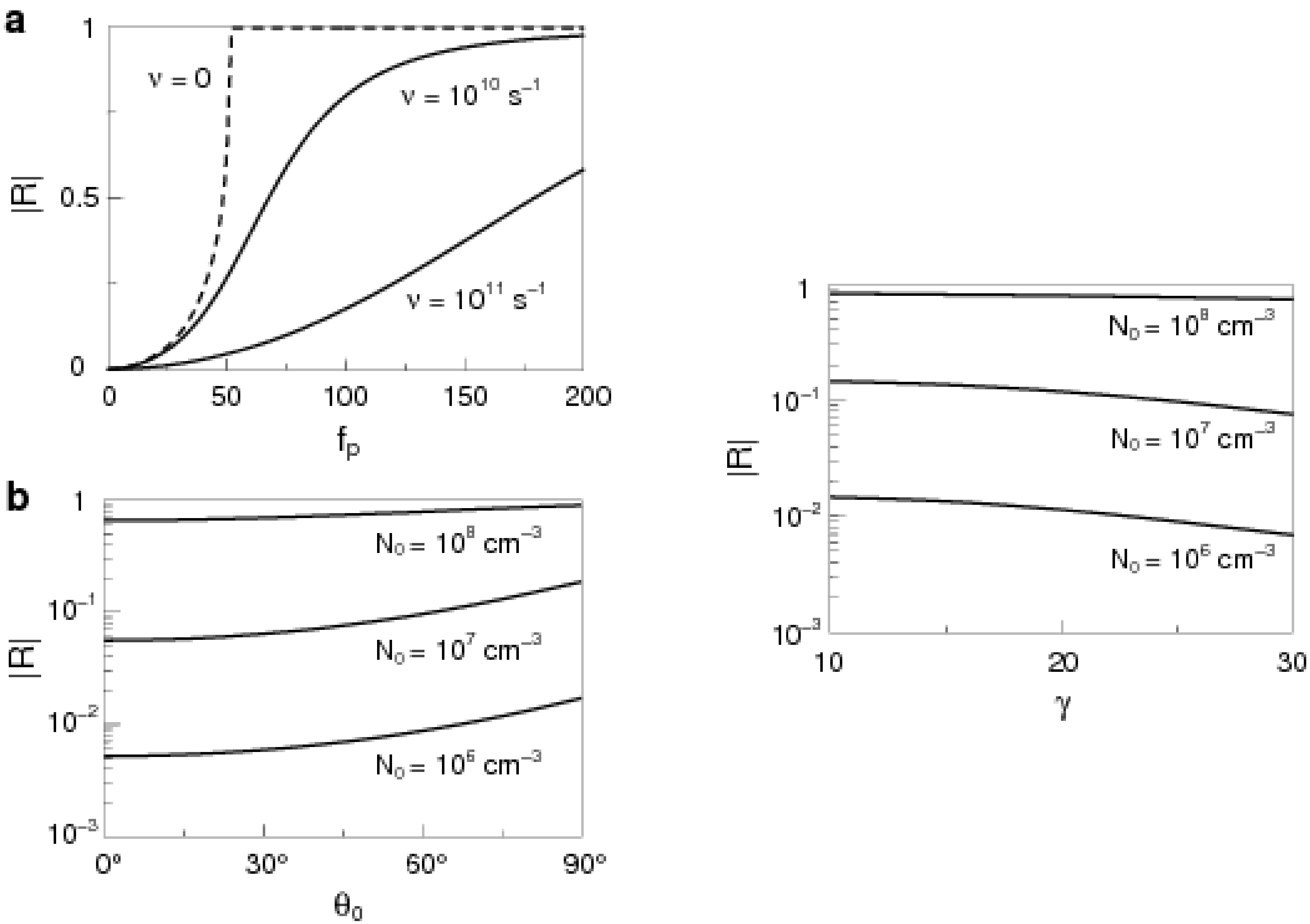
1 MHz incident wave

- The following results are for work done with 1 MHz incident wave:
  - In this case the received incident frequency in the moving front reference frame still is smaller than the size of the front.
  - The results from this work have been submitted for publication to Astroparticle Physics Journal.




a
b
|R|
μ⁻¹(ns)
N0 = 10^8 cm^-3
N0 = 10^7 cm^-3
N0 = 10^6 cm^-3
ν = 0
ν = 10^10 s^-1
ν = 10^11 s^-1
0.01
0.1
1
10


a
b
Re f_t1, Im f_t1
Re f_t1
Im f_t1
Re f_t2, Im f_t2
Im f_t2
Re f_t2
f_p
0
50
100
0.5
3·10^3
2·10^3
10^3



a
ν = 0
ν = 10^10 s^−1
ν = 10^11 s^−1
|R|
1
0.5
0
0
50
100
150
200
f_p
b
N_0 = 10^8 cm^−3
N_0 = 10^7 cm^−3
N_0 = 10^6 cm^−3
|R|
1
10^−1
10^−2
10^−3
0°
30°
60°
90°
θ_0
N_0 = 10^8 cm^−3
N_0 = 10^7 cm^−3
N_0 = 10^6 cm^−3
|R|
1
10^−1
10^−2
10^−3
10
20
30
γ

Prospect for Detection (Returned Power)

- Power of the returned signal

$$P_r = \frac{P_e A|R|^2}{2\pi r^2 (1+\frac{r\cos\theta_0}{R_c})^2}$$

where R_c is the curvature of the front ~7km,

P_e is the power from transmitter (we assume P_e=200 kW)

- R is the reflection coefficient ~0.075 for
  - Plasma density $N_0=10^7 cm^{-3}$, collision frequency $\nu=10^{10}\ s^{-1}$, $\gamma=30$, $\theta_0=45^0$, and incident frequency $\omega_0/2\pi=1$ MHz
- A is the effective area of the receiving antenna (we assume $A=3\times10^{-3}\ m^2$ for a typical antenna).
- r is the distance from transmitter to ionization (r~10 km).
- The reflected power P_r is then: ~1.3nW ~ -58.9dBm and reflected frequency $\omega_r/2\pi=3.07$ GHz

Prospect for Detection (Noise and Bandwidth)

- For 3 GHz receiving frequencies, the total system temperature is T_N ~50 K, the noise power per unit bandwidth is $p_N = kT_N \sim 7\times10^{-22}$ W/Hz
  - We set the condition for detection as $P_r = p_N \Delta\omega_r$, which yields **$\Delta\omega_r$=2THz**
- The bandwidth of the signal is given by

$$\frac{\Delta\omega_r}{\omega_r} = \frac{\Delta\omega_0}{\omega_0} + \frac{\sin\theta_0 \Delta\theta_0}{1+\cos\theta_0} + \frac{2\Delta\gamma}{\gamma}$$

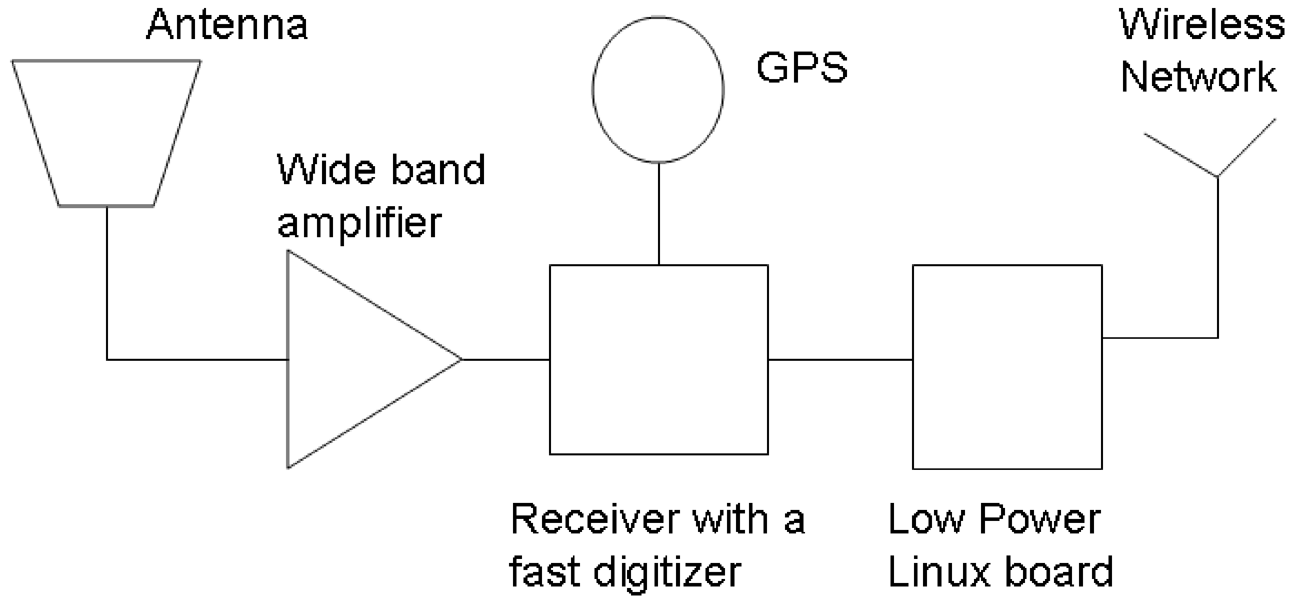
  - The bandwidth presented above ~2 THz is much larger than the combined broadening of the spectrum due to
  - incident frequency bandwidth,
  - due to variation of incident angle,
  - and due to variation of Lorentz factor in the downward propagation.
- **Therefore the 1 MHz makes for more suitable detection environment.**

Conclusions

- Radar detection of high energy cosmic rays by detecting the reflected signal off the ionization front was investigated for two different incident frequencies 10 MHz and 1 MHz.
- The reflected waves in both cases are collimated towards the axis of the shower.
- Both models properly account for the relativistic Doppler effect.

- While the 10 MHz case showed promise the 1 MHz incident wave is more suitable for High Energy Cosmic Ray Detection because:
  - **Power is about 4 orders of magnitude higher than 10 MHz;**
  - **The system noise temperature at the expected reflected frequency of 3 GHz was smaller in the sweet spot between atmospheric absorption and galactic noise.**
- R & D is necessary to understand the noise better and ultimately run concurrently with a ground array, where the ground array triggers the radio receiver.

Future Prospect



Schematic of hardware for one station.

- Develop the hardware and deploy at a traditional array.
- Run concurrently with the array either by receiving a trigger when a cosmic rays shower from ground array or run standalone via GPS time tagging