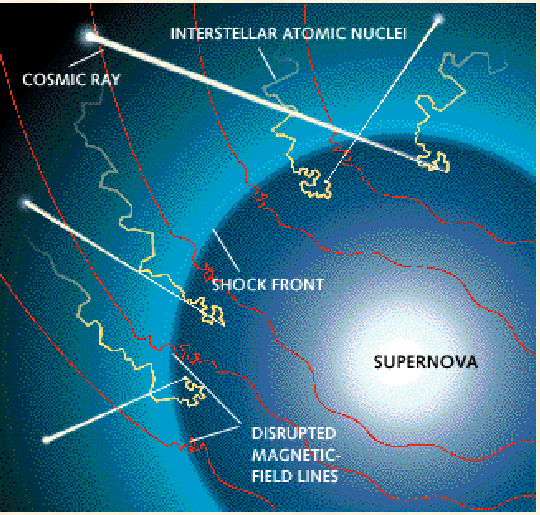
Ultra-High Energy Cosmic ray and Neutrino Physics using the Moon

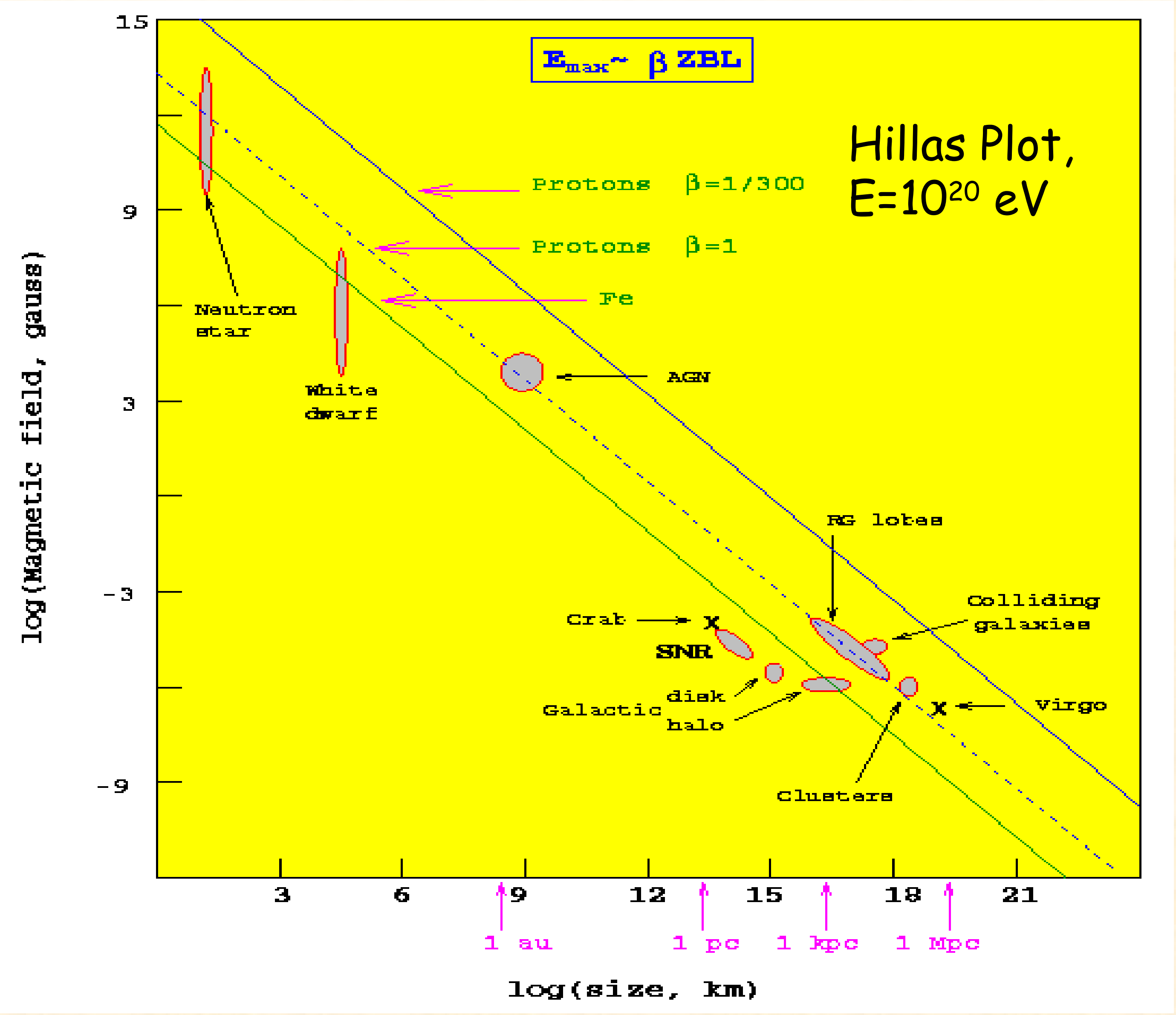
Olaf Scholten
KVI, Groningen

Shock wave acceleration

Particle crosses shock boundary many times, picking up energy on each passage.



J.W. Cronin et al.
Sci. American, 1998.



Topological Defects or SUSY particles

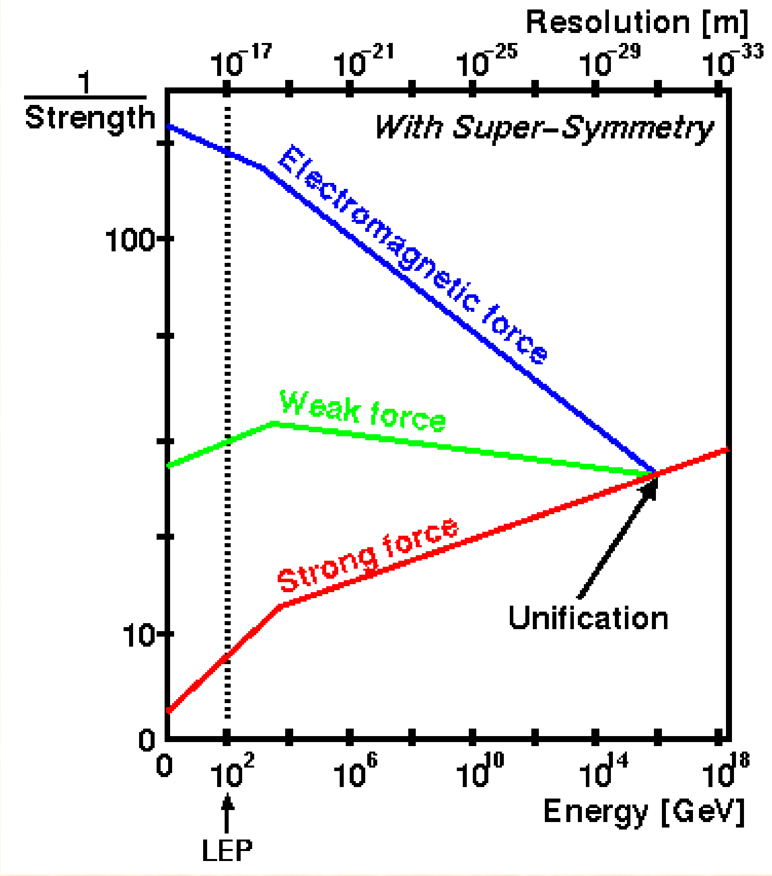
Possible “relic” particles (dubbed X)
due to symmetry breaking phase transitions in the early Universe

Part of Dark Matter ?

Masses at the GUT scale (M_X~10^{25} eV)
or at the Planck scale (10^{28} eV).

Decay or annihilation
X → jets → protons

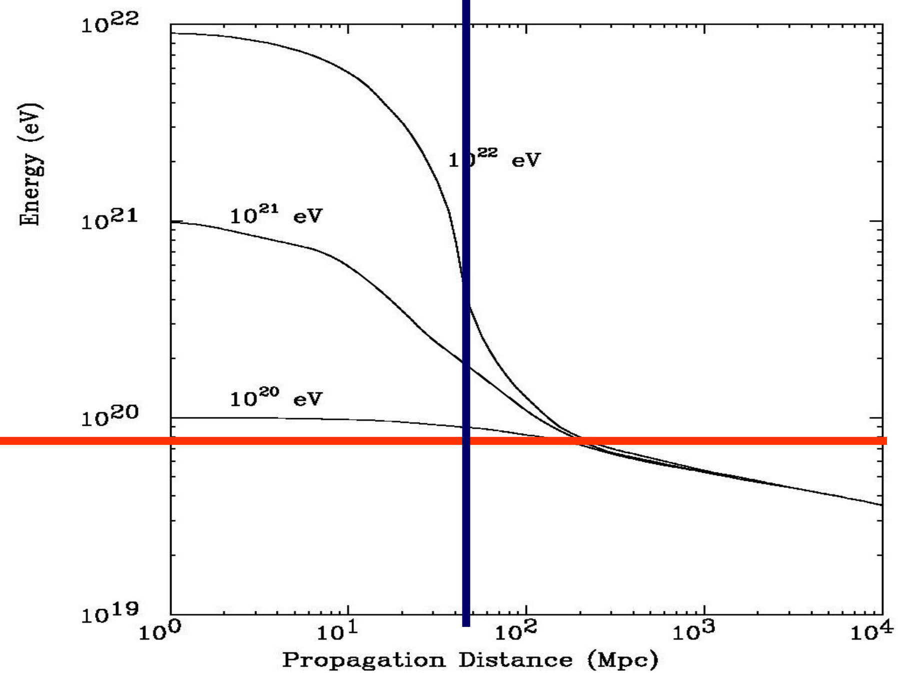
X → leptons or
→ all neutrinos



Greisen – Zatsepin - K'uzmin (GZK)

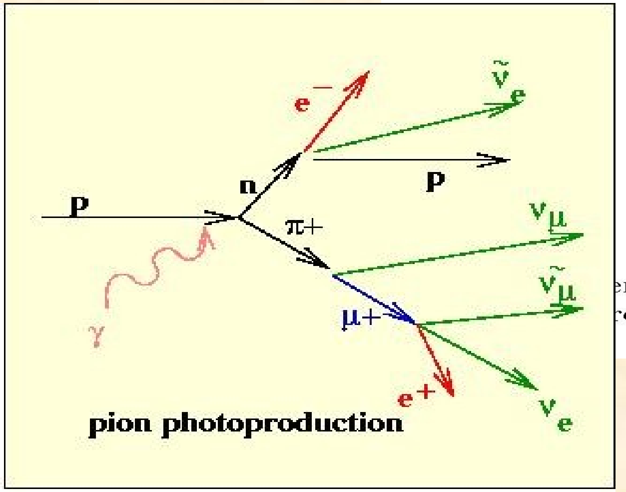
The GZK Distance

Energetic protons loose energy through Interactions with the cosmic microwave background



ergy of a proton as a function of the propagation distance through the 2.7K
round radiation for various initial energies.

The GZK Energy



Ultra High Energy Cosmic Rays

Physics Issues & Signatures

Bottom up models (cosmic accelerators):

- Distinct sources, strong angular correlations above GZK

Top-Down models (decay DM particles):

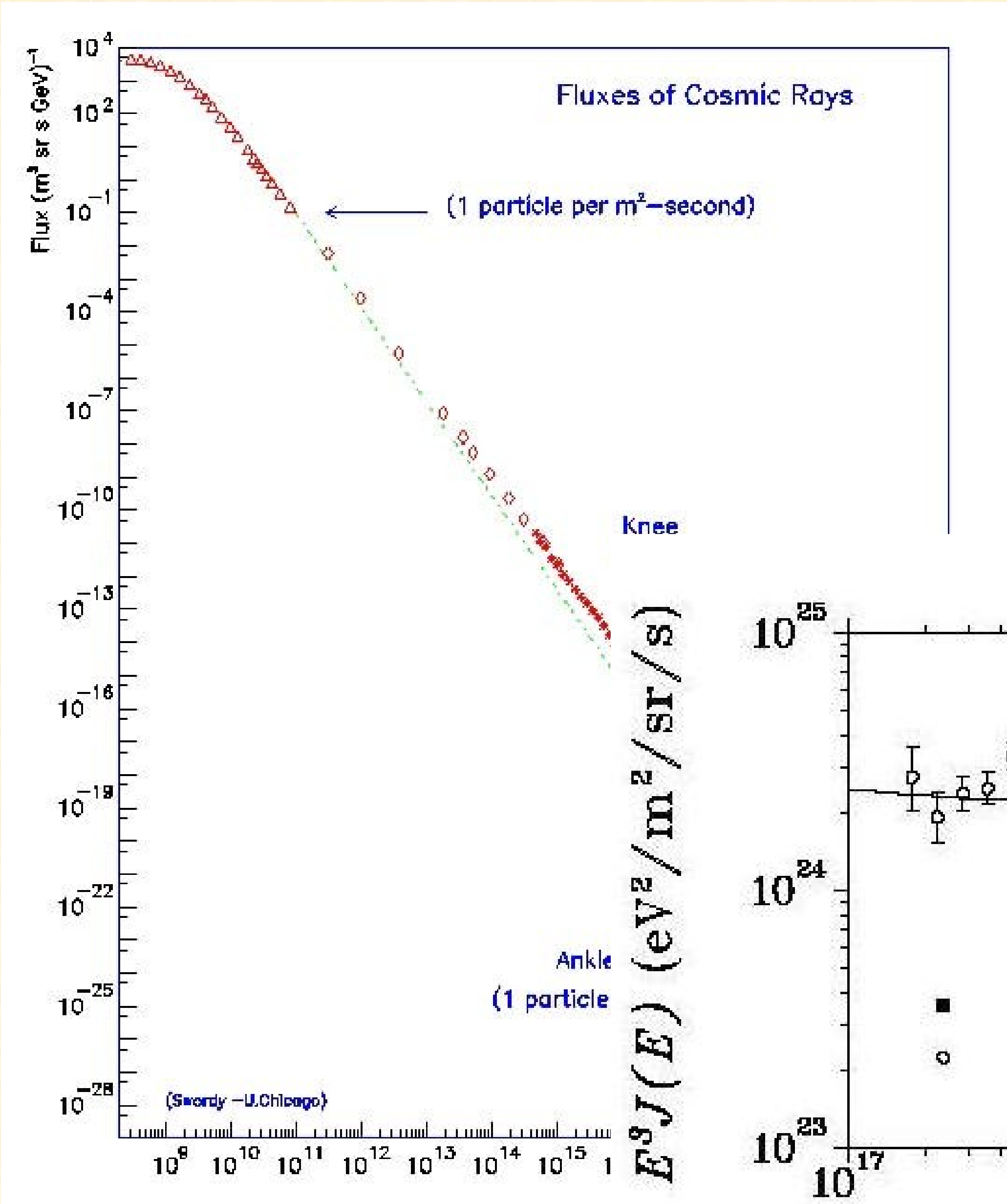
- Diffuse source
- Mixture of different particle species

$E>10^{20}$ eV

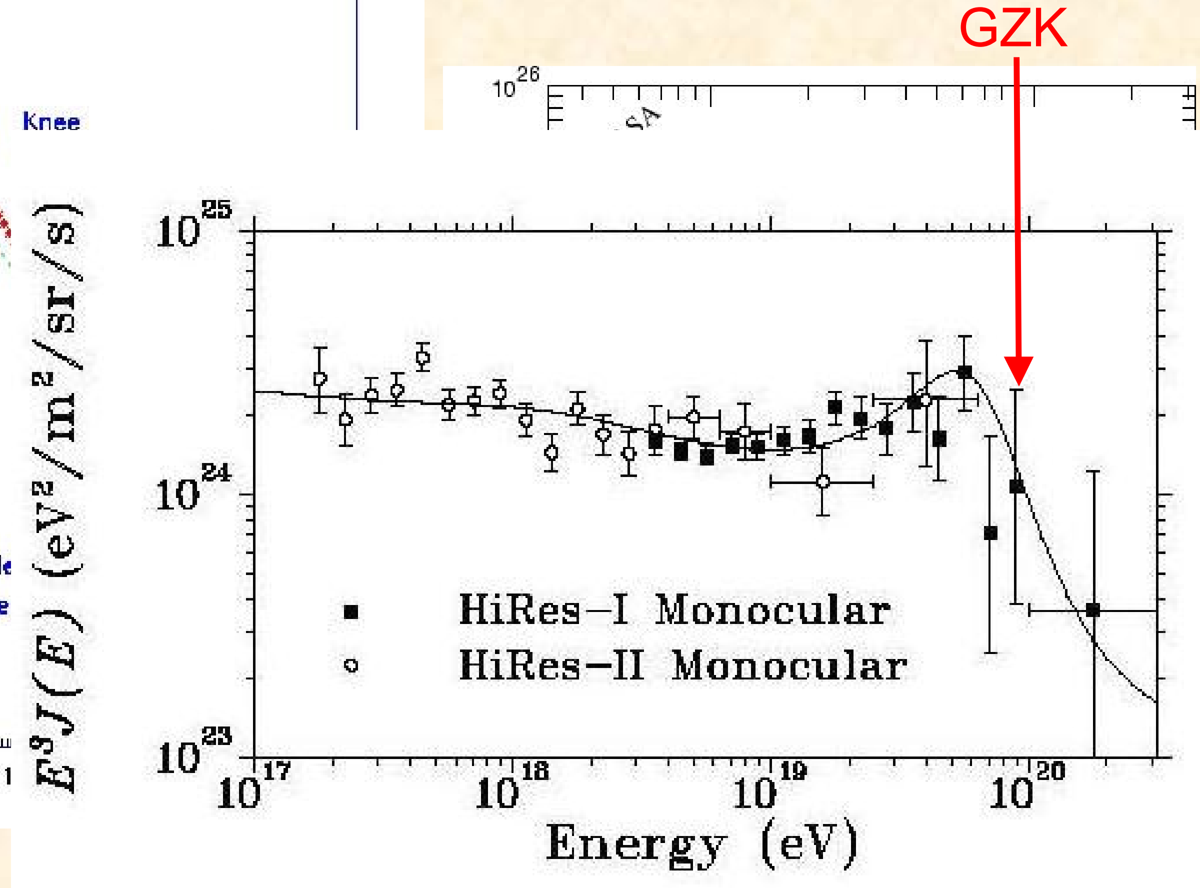
GZK cutoff, based on Lorentz Invariance:

- Cut-off in CR spectrum at $E>6\ 10^{19}$ eV hadrons
- Neutrino flux from pions decay

Low Flux Challenge



≈ 1 / km^2 / sr / century
above 10^{20} eV!



15/06/07

Think Large

Cosmic ray Detection

Use the Moon!!

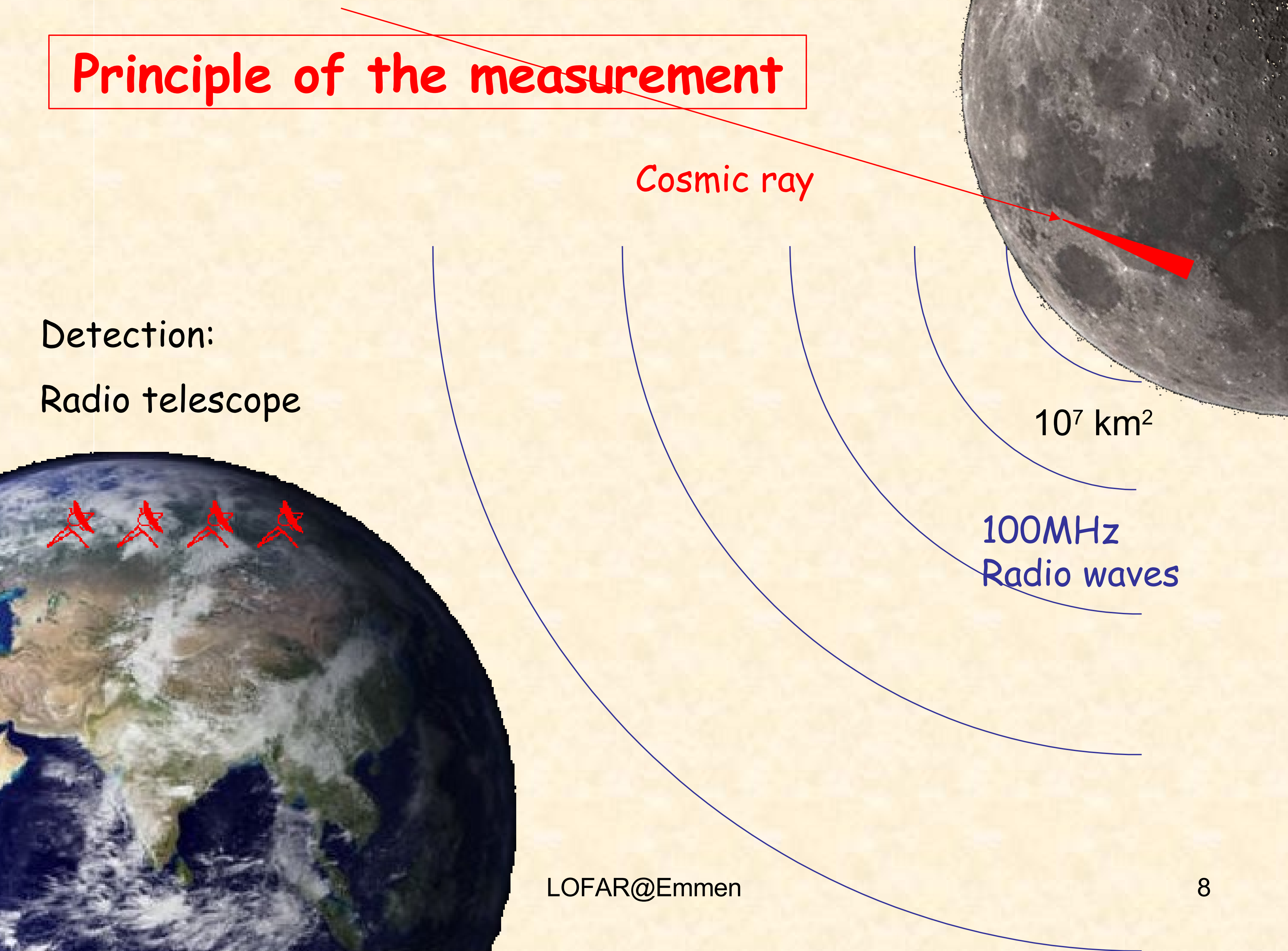
Area = $2\ 10^7\ km^2$

Figure 1: Astronaut pushing rover uphill. Broken boulder at station 6, Apollo 17. Boulder tracks lead back up North Massif. NASA# AS-17-164-5954.

Principle of the measurement

Detection:

Radio telescope



Radio emission Mechanisms

- In air: Geo-synchotron radiation

  Coherent emission in Atmosphere

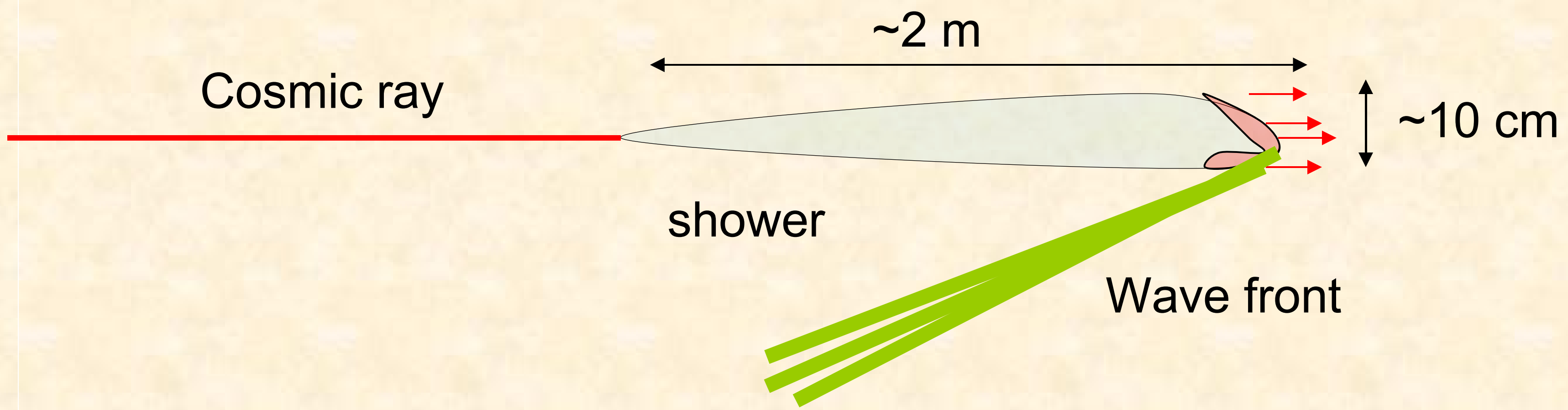
  LOPES
- In matter: Askaryan effect

  Coherent Čerenkov emission in

  ice, salt, rock, ….

  FORTE, RICE, SALSA, GLUE,

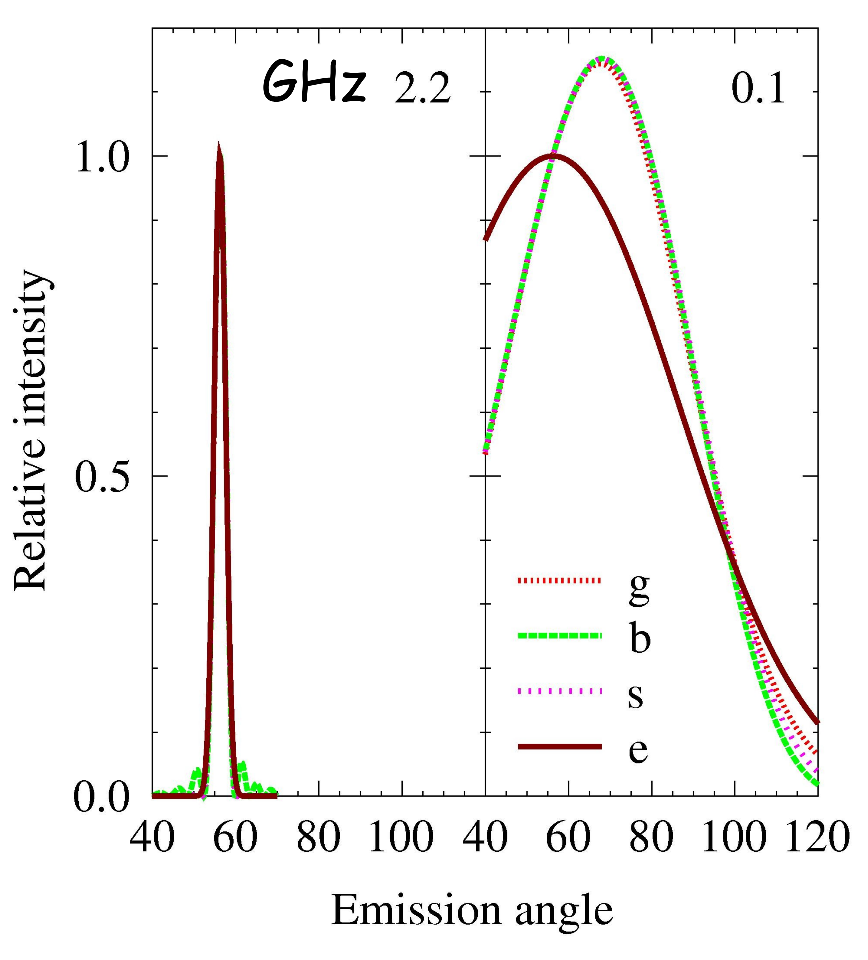
Askaryan effect: Coherent Cherenkov emission



- Leading cloud of electrons, $v \approx c$
  - Typical size of order 10cm
  - Coherent Čerenkov for $\nu \leq$ 2-5 GHz
  - $\cos\theta_c = 1/n$, $\theta_c = 56^o$ for ∞ shower length
- Length of shower, $L \approx$ few m
  - Important for angular spreading

Spreading around Cherenkov-cone

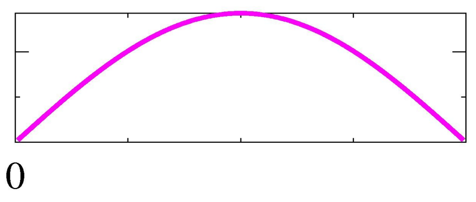
n=1.8



O.S. etal., Astropart.Phys. 2006

Sine profile

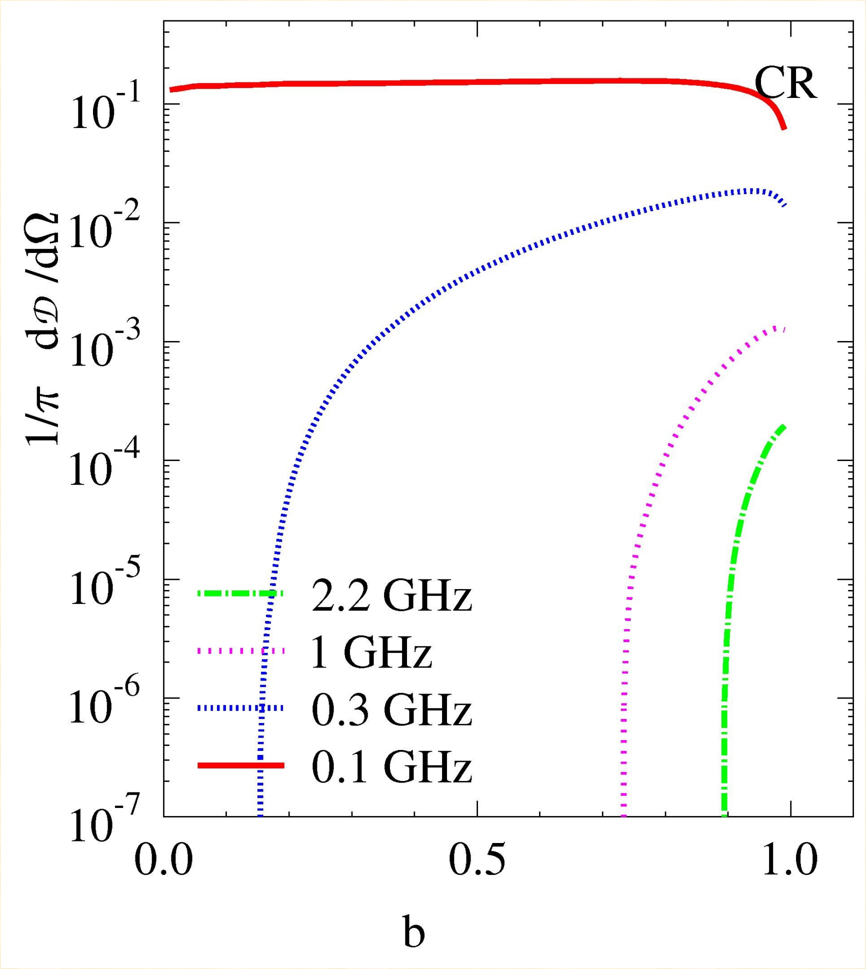
L=1.7 m , E=10^{20}



$$\chi = (n \cos\theta - 1)L/n\lambda$$

$$I_s(\theta) = \left[\frac{\sin\theta}{\sin\theta_c}\frac{\cos\pi\chi}{(1-2\chi)(1+2\chi)}\right]^2$$

Cosmic rays, Position on Moon



Partial Detection probability

Normalized distance from center

Calculations for

E_{cr}=4 10^{21} eV

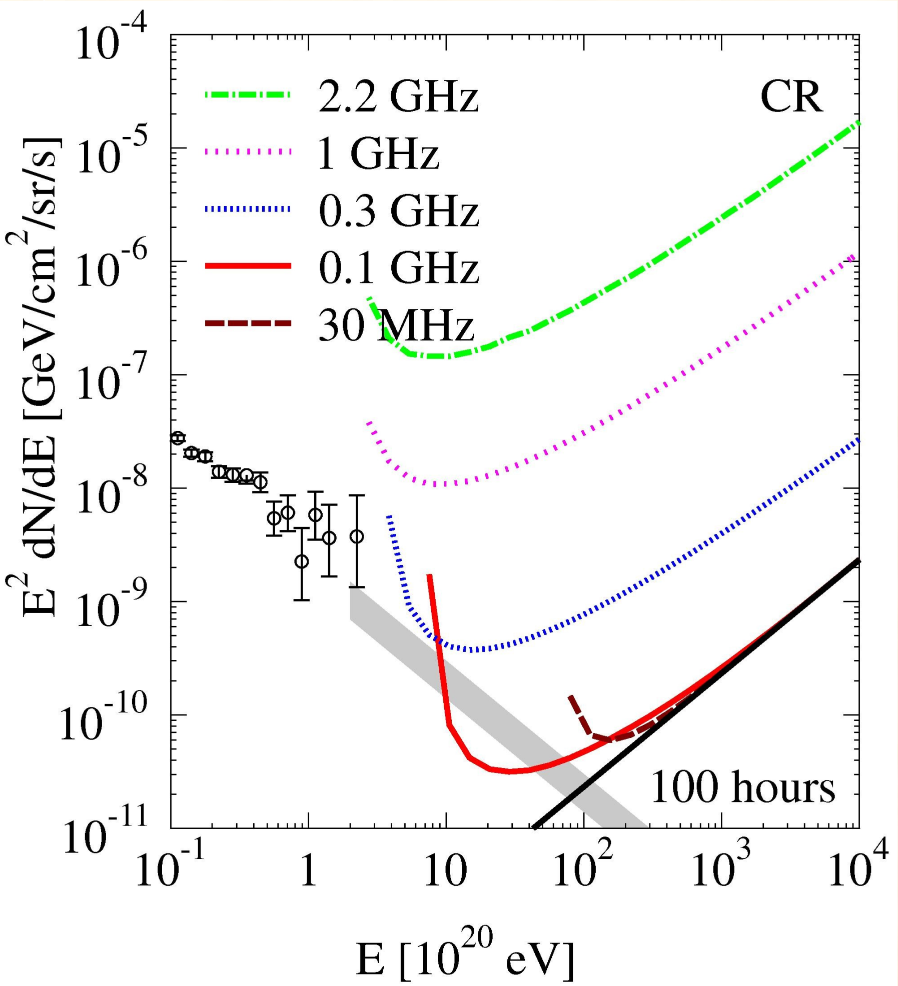
With decreasing ν :

- increasing area
- increasing probability

∫ over surface Moon

$D \propto \nu^{-3}$

Detection Limits, Cosmic rays



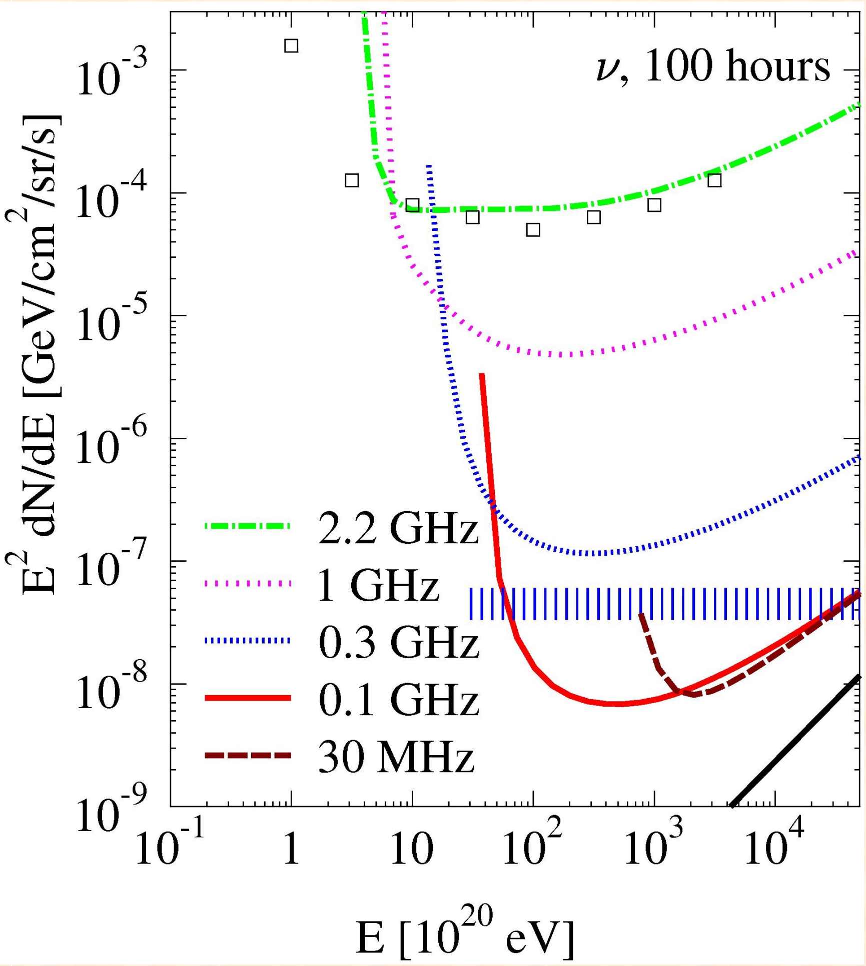
Minimum Flux for detecting

1 count/100h

Detection threshold = 500Jy

- Decreasing ν :
  - Increasing threshold like ν^{-1}
  - Increase sensitivity like ν^{-3}

Detection Limits, Neutrinos



Present results compared with that of GLUE experiment (@2.2GHz)

Waxman-Bahcall limit

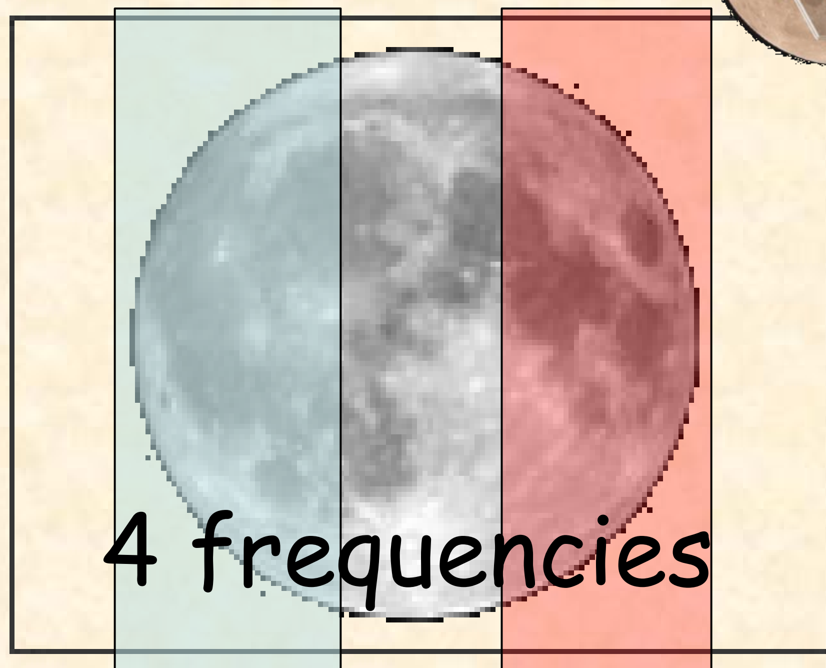
NuMoon Experiment

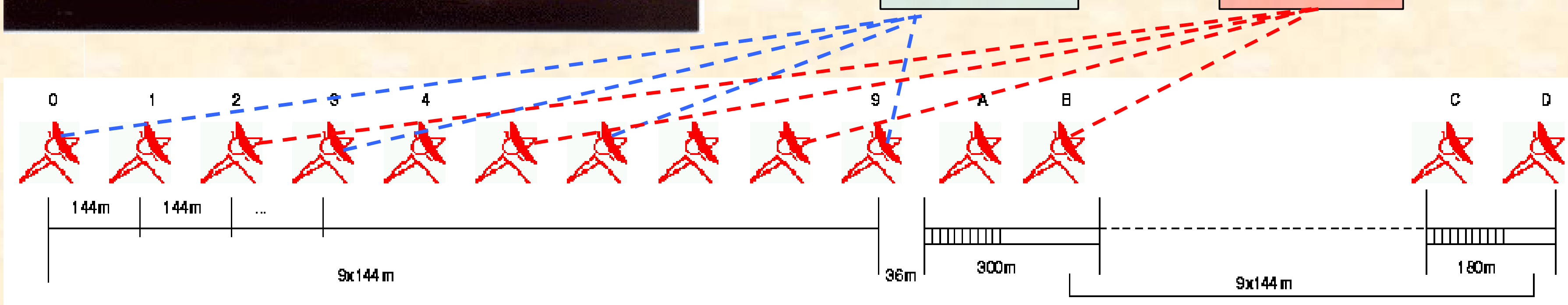
- Use 100-200 MHz window
- Moon: radius=1700 km; area = 2 10^7 km^2
- Low Attenuation: λ_r= 9[m] / ν [GHz]

NuMoon Experiment @ WSRT

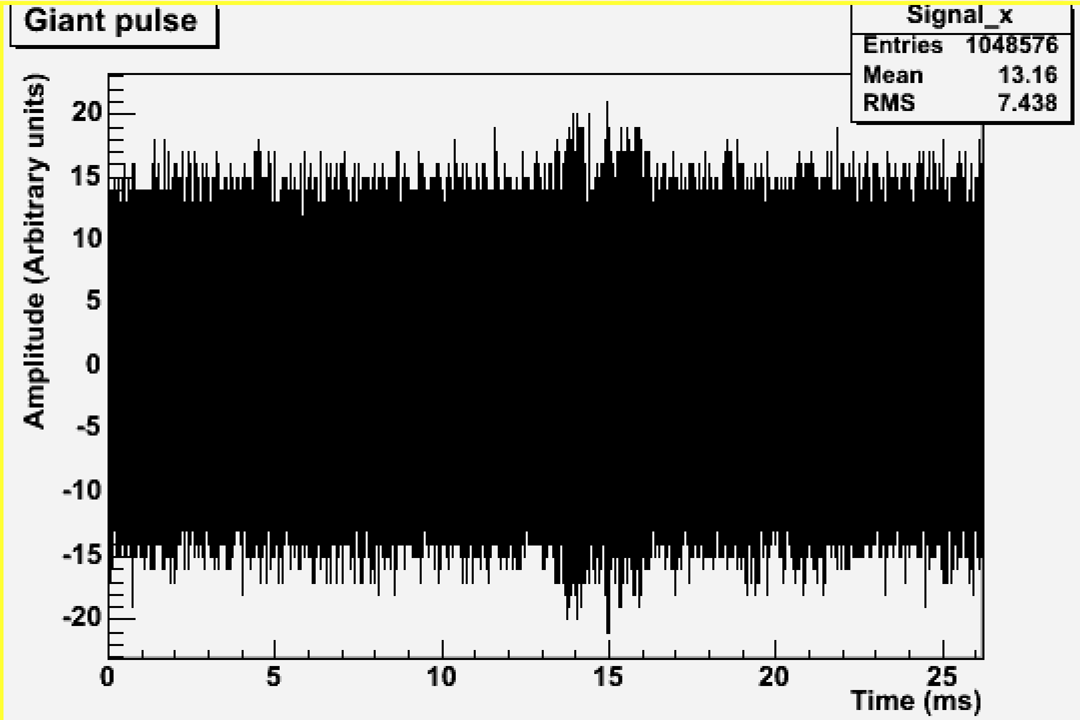
117-175 MHz, PUMA

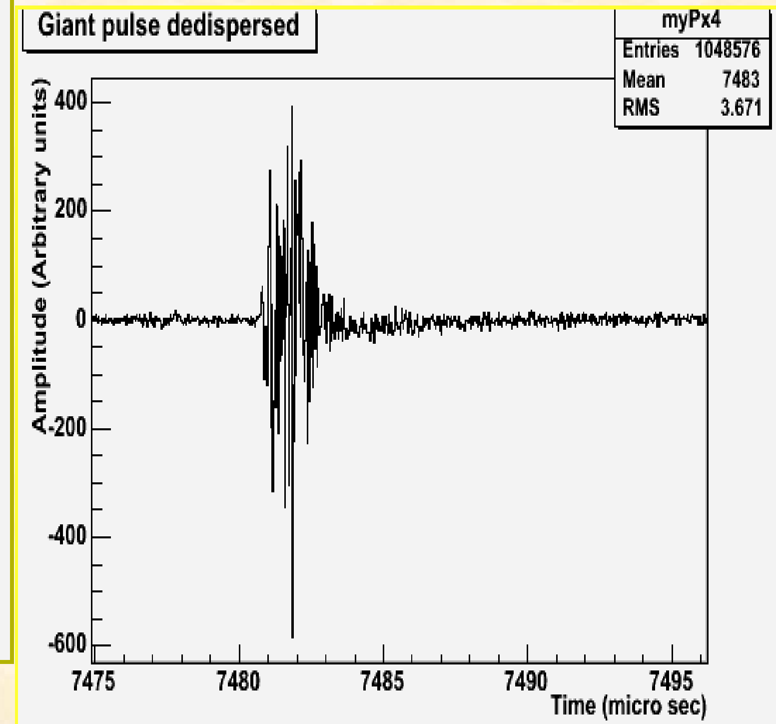
Use Westerbork radio observatory





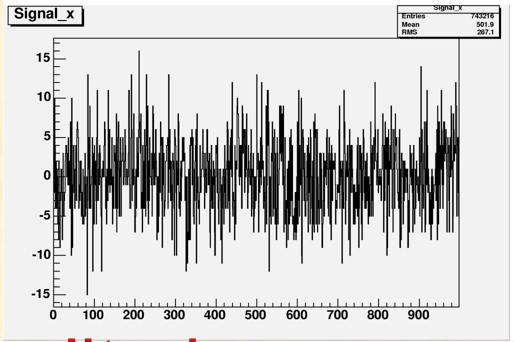
Processing Pipeline





- 18 TB raw data per 6 hr slot
- Excision of narrow-band interference
- De-Dispersion of ionosphere with GPS TEC values
- Indentification of peaks in time spectrum (50 ps)

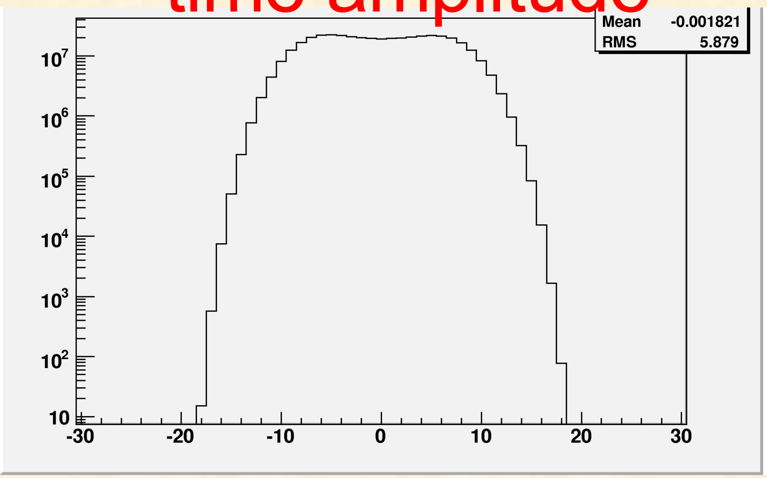
Observations

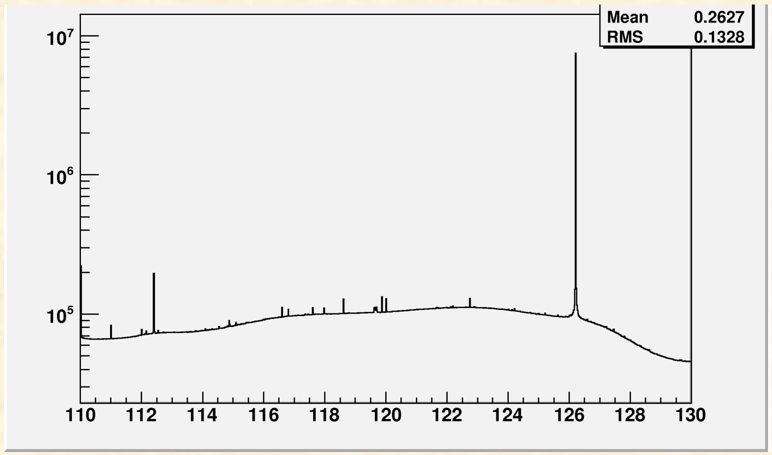


Frequency spectrum

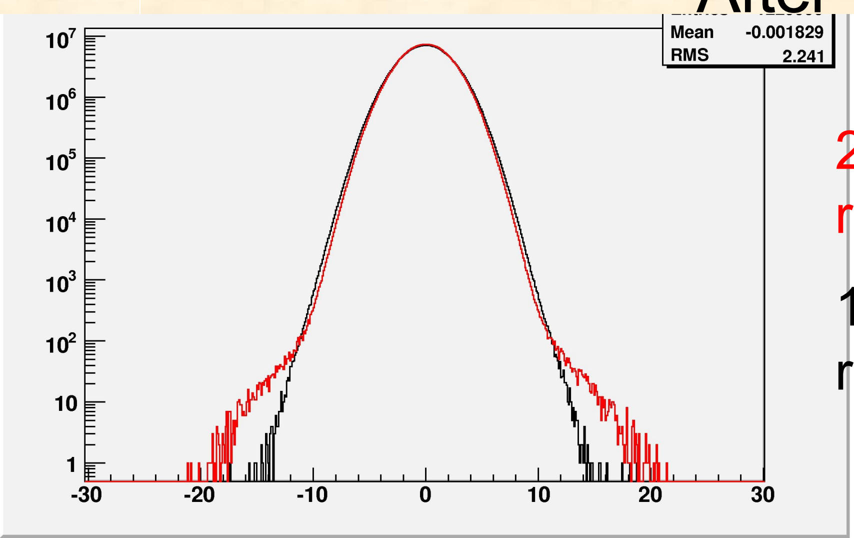
time amplitude

raw data





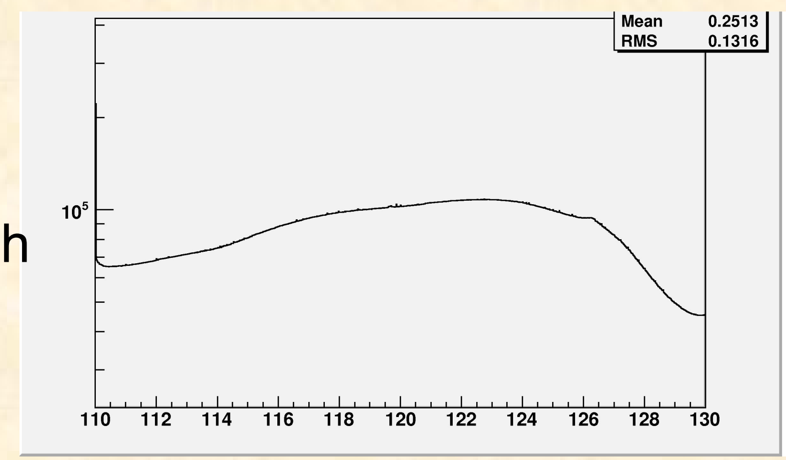
After Removing RFI



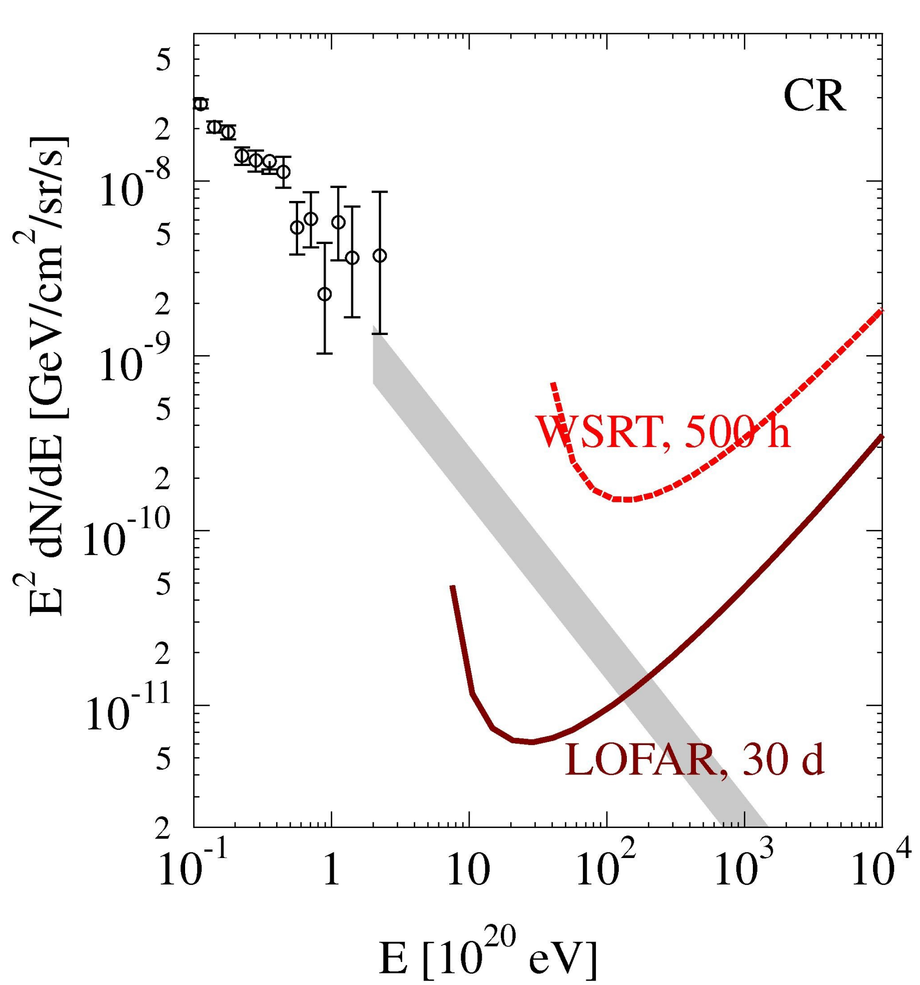
20 kHz, low resolution

1.5 kHz, high resolution

OFAR@Emmen



Cosmic Rays



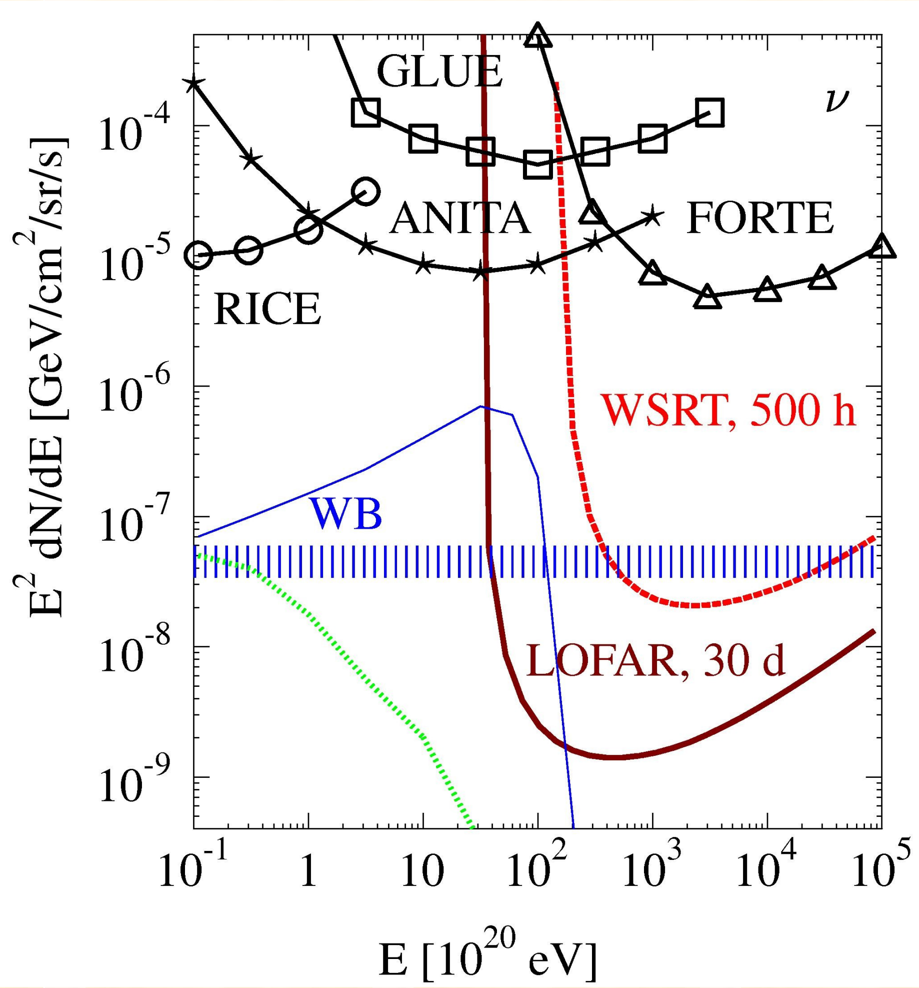
Sensitive to flux beyond GKZ limit

Detection threshold taken at F_{det}= 25 F_{noise}

WSRT: F_{det} = 15,000 Jy

LOFAR: F_{det} = 500 Jy

Neutrinos



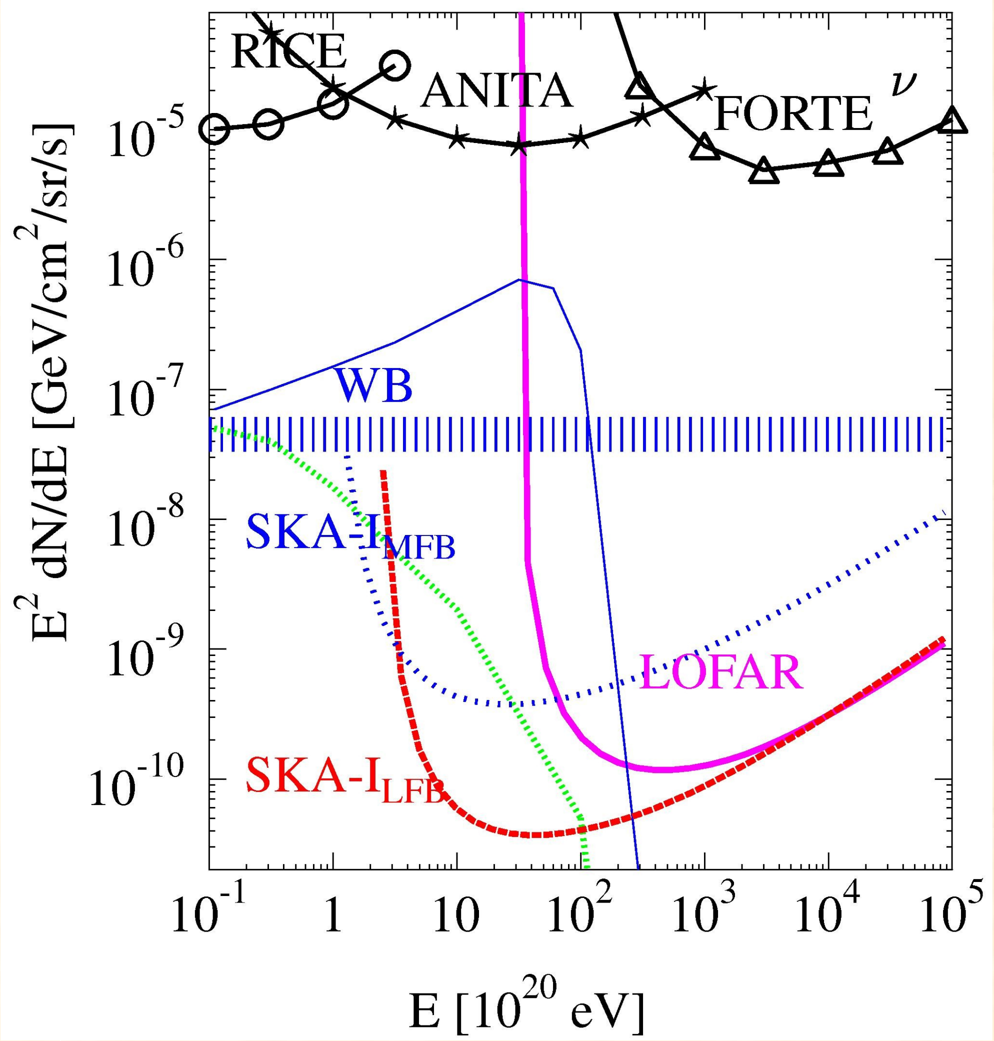
Theoretical predictions:

Waxman-Bahcall limit

GZK induced flux
Phys.Rev.D64(04)93010

Topological defects
AstroPhys. J. 479(97)547

Future: SKA,LORD

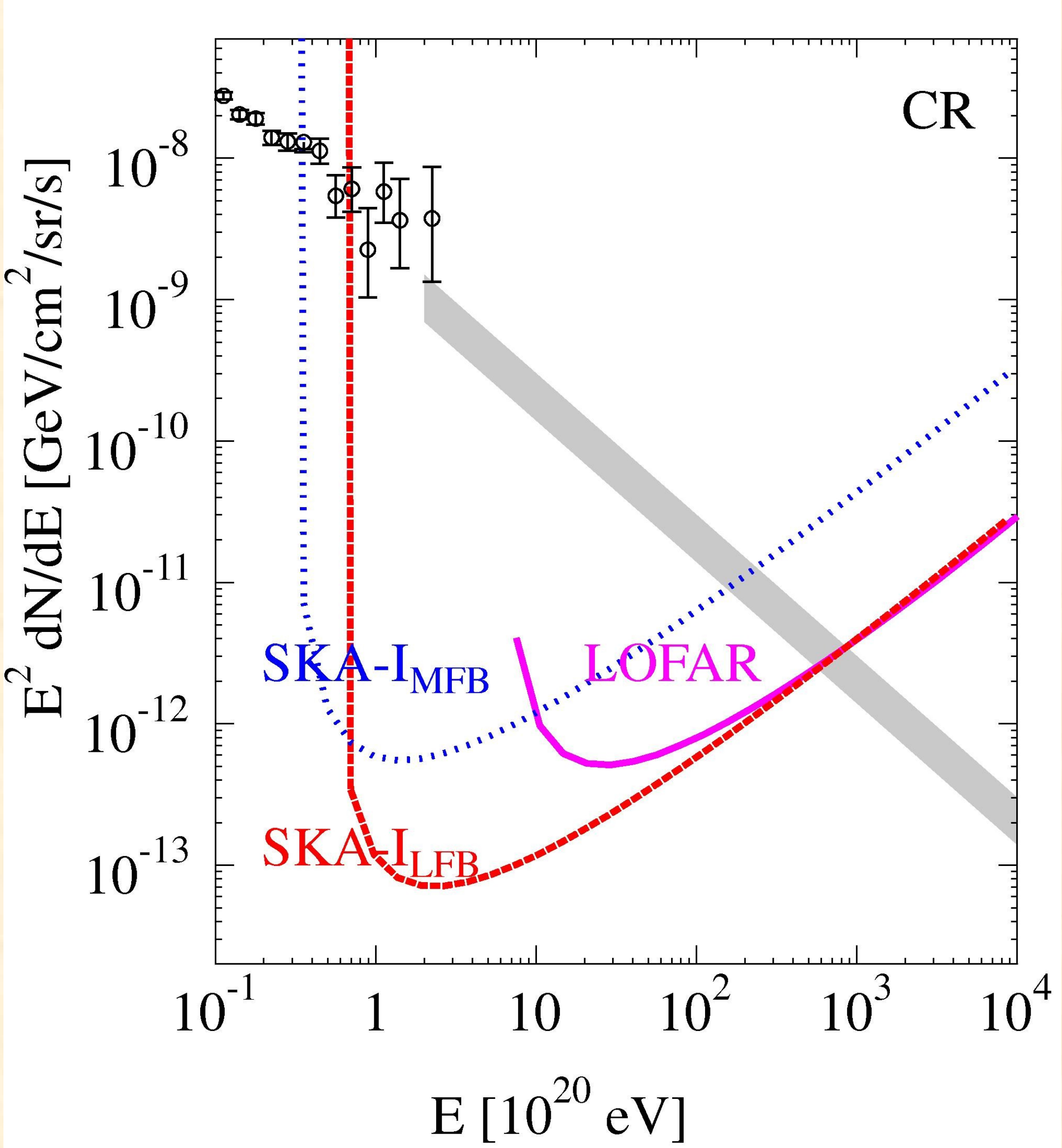


1 year observation,

LFB: 100-300 MHz

MFB: 300-500 MHz

SKA-Hadrons


CR
SKA-I$_{MFB}$
LOFAR
SKA-I$_{LFB}$
E^2 dN/dE [GeV/cm^2/sr/s]
E [10^{20} eV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-1}
1
10
10^2
10^3
10^4

NuMoon @ WSRT: Aquiring data

Within 1 month competitive

Unprecedented (10^few) sensitivity to

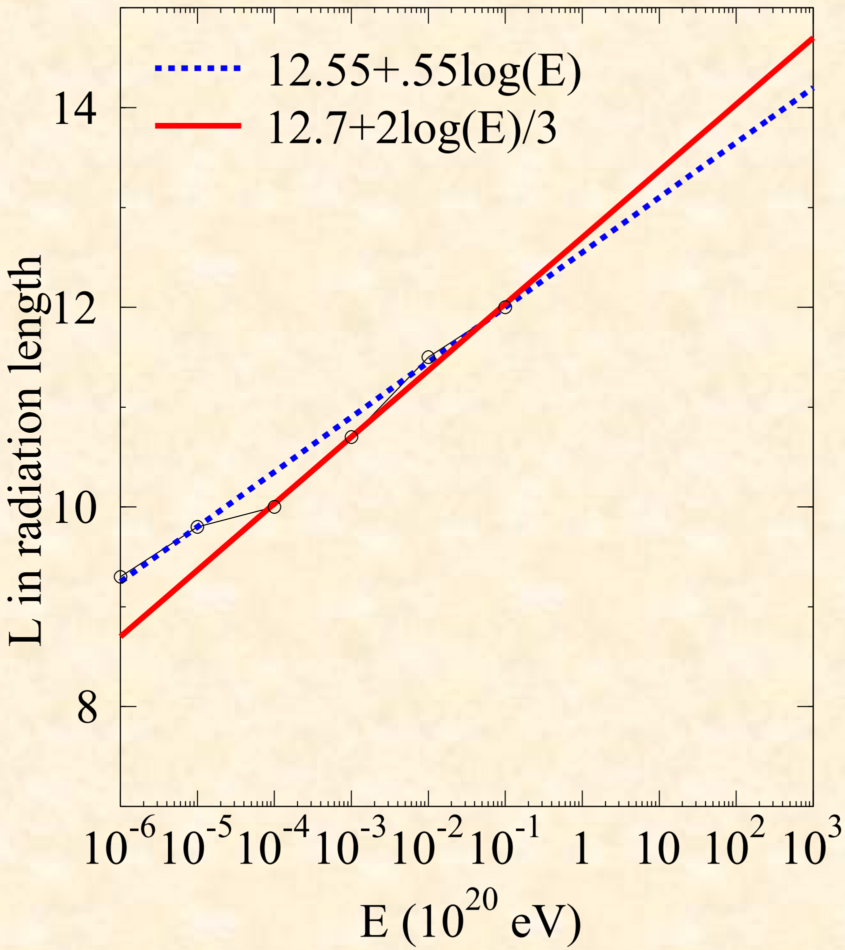
UHE cosmic rays and neutrinos

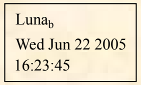
NuMoon embedded in KSP3

Future:

NuMoon @ SKA

Shower length





The physics case

Evidence for
Ultra High Energy Cosmic Rays
> GZK cutoff

- Production-acceleration mechanisms?
- Intergalactic Transport (GZK)
- Quest for nearby sources (<50 Mpc)

Challenging rate: ≈ 1 / km^2 / sr / century above 10^{20} eV!

Some distance scales

• Nearest star, Proxima Centauri – 4 LY

• Diameter of our galaxy – 100,000 LY

• Distance to nearest galaxy – the Sagittarius dwarf galaxy, which is being "eaten" by the Milky Way – 80,000 LY

• Size of our "Local Group" – a collection of at least 30 galaxies, including Andromeda – 3 Million LY

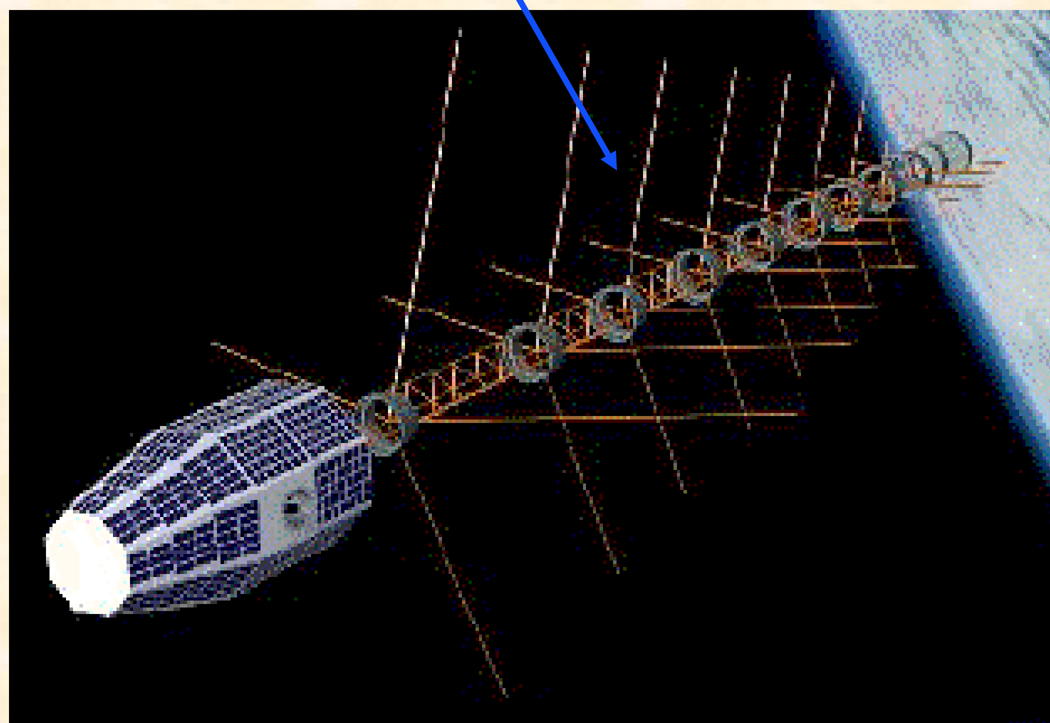
• Size of our "Local Supercluster" which contains our Local Group, the Virgo Cluster, and others – 100 Million LY

1pc = 3.26 LY

FORTE satellite
(Fast On-orbit Recording of Transient Events)

- Main mission: synaptic lightning observation
- Viewed Greenland ice (1997-99)
  - 1.9 MILLION km^3
  - 38 days

Log-periodic antennas



N. Lehtinen et al., PRD 69, 013008 (2004)

Calculations for

E_{cr}=4 10^{21} eV

Influence of frequency

Case:

Shower @ 2.5^0 with surface

0.1 GHz

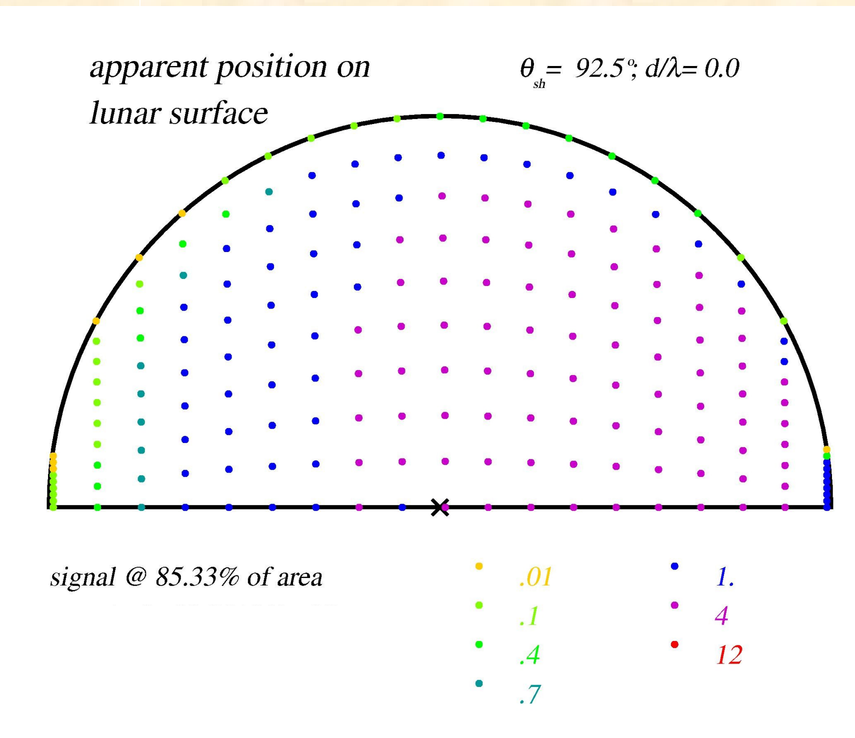
85% of area

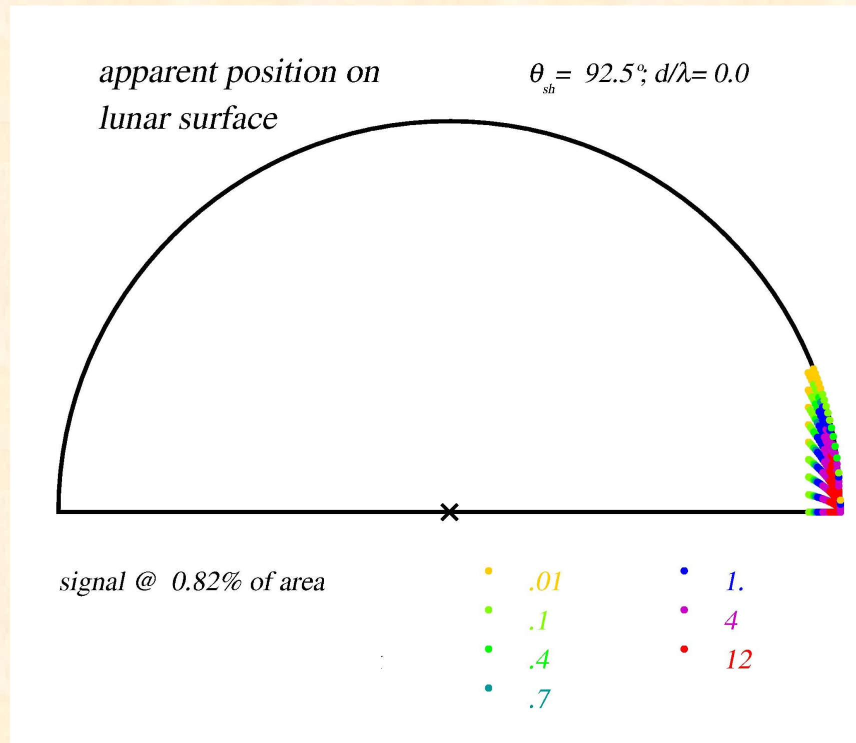
Simulations for Moon

2.2 GHz

0.8% of area

Minimal signal = 3000Jy





Intensity v.s. cos θ, φ