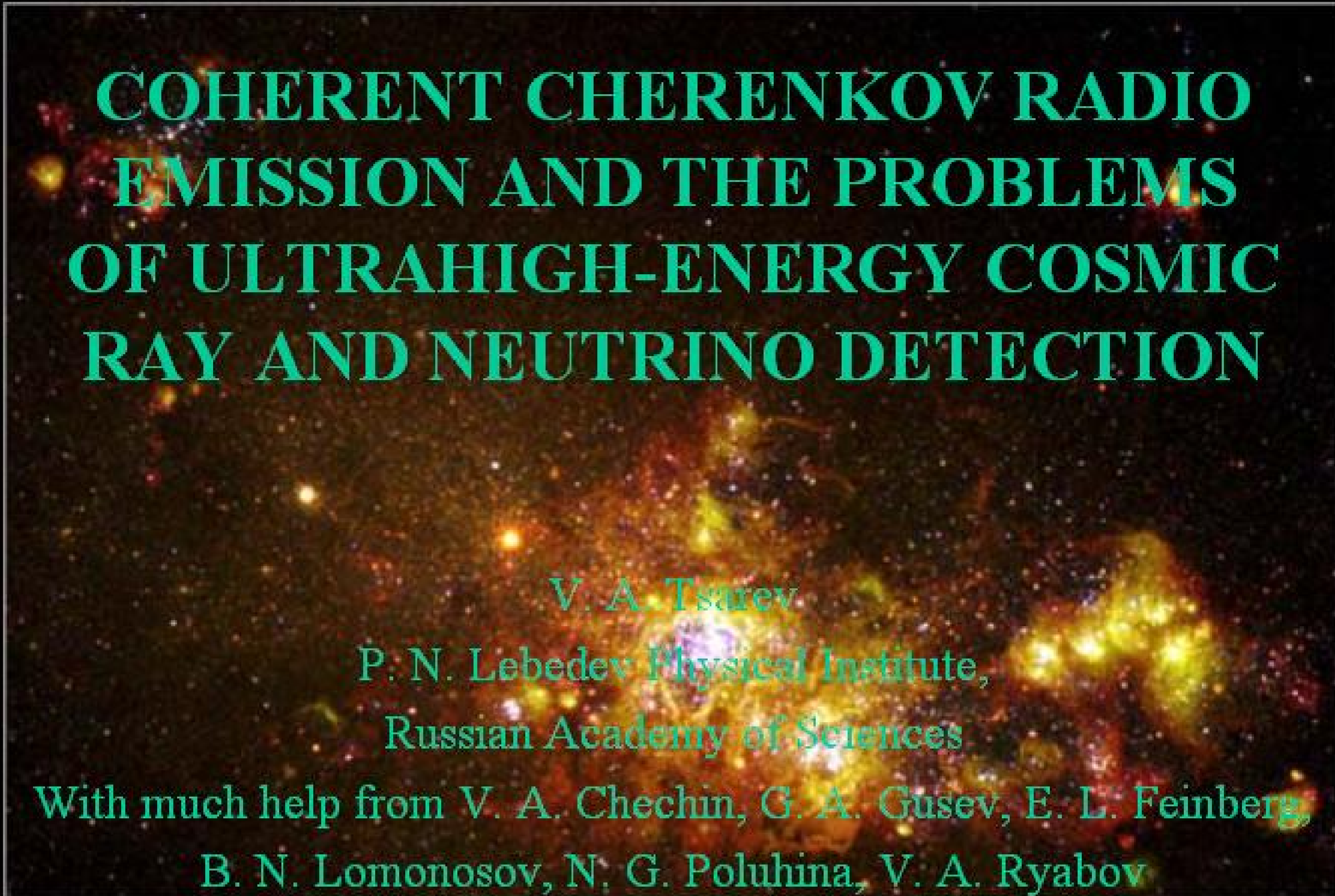


COHERENT CHERENKOV RADIO EMISSION AND THE PROBLEMS OF ULTRAHIGH-ENERGY COSMIC RAY AND NEUTRINO DETECTION

V. A. Tsarev

P. N. Lebedev Physical Institute,

Russian Academy of Sciences

With much help from V. A. Chechin, G. A. Gusev, E. L. Feinberg, B. N. Lomonosov, N. G. Poluhina, V. A. Ryabov

Traditionally

Cherenkov radiation is associated with **optical range**

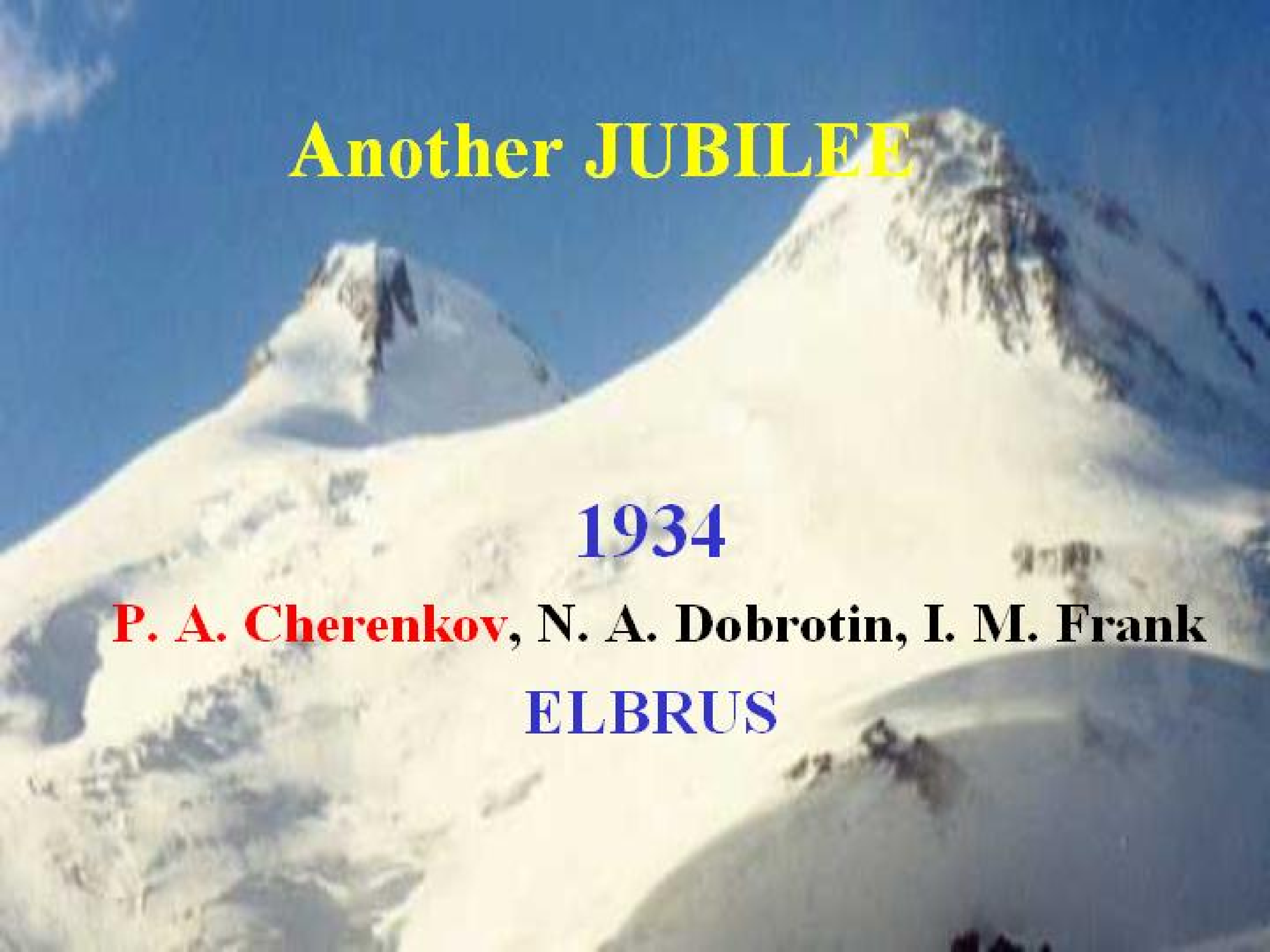
"Non-traditional":

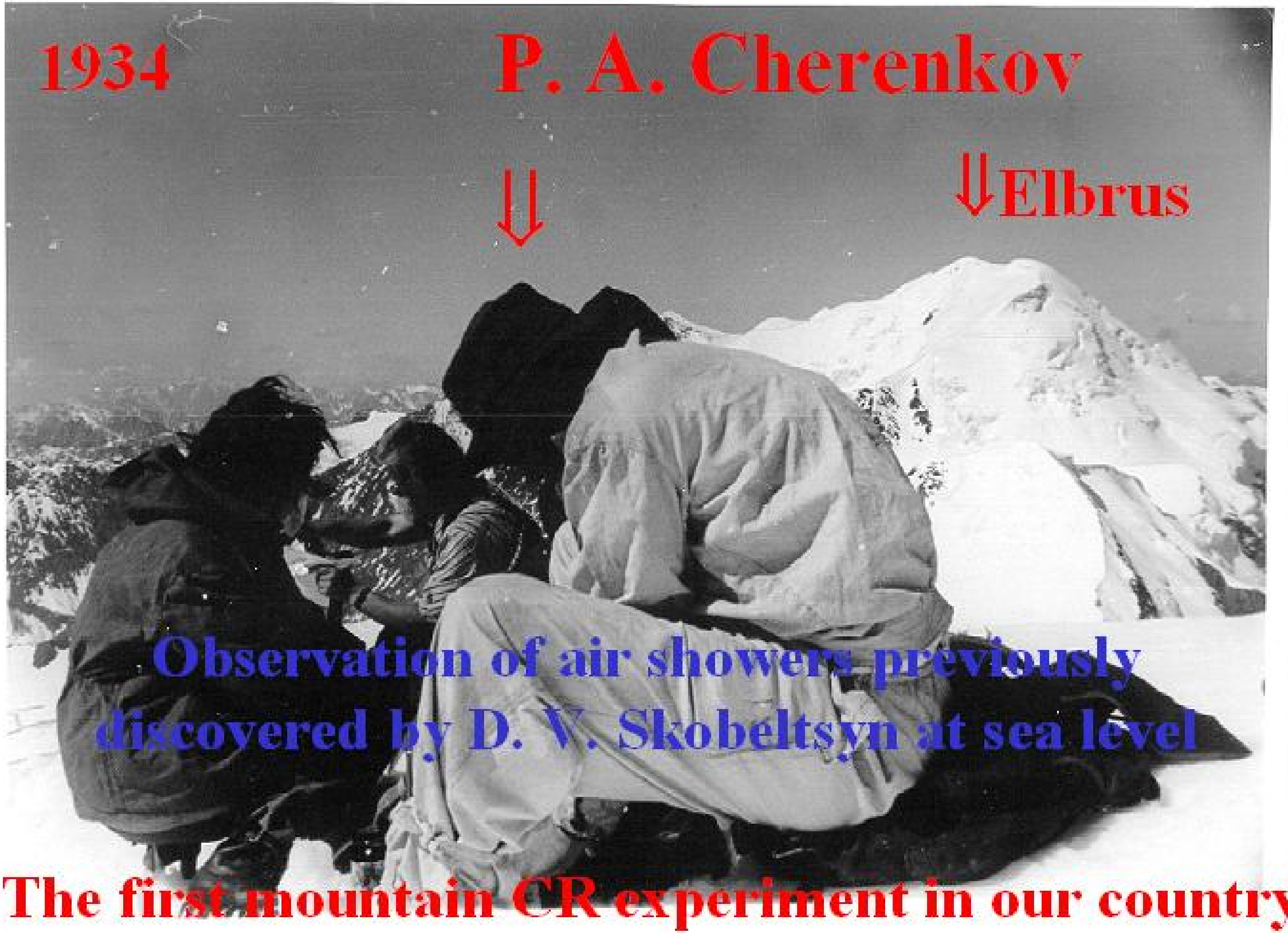
radio-frequency band

Recently – great interest –

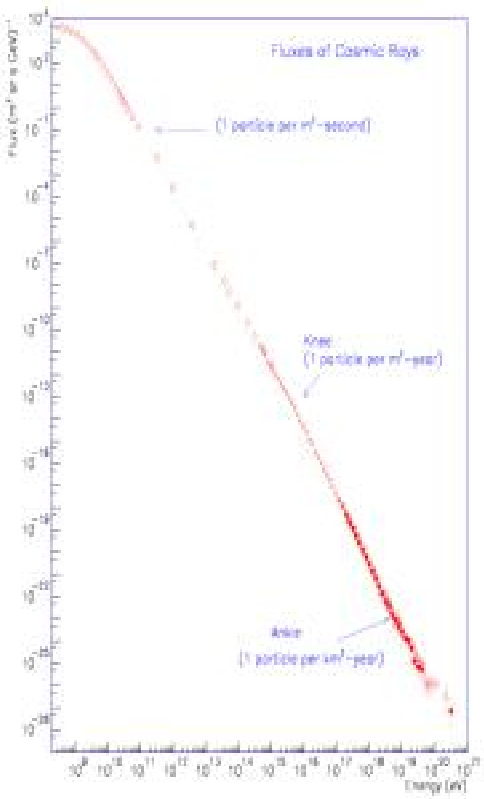
hope for a progress in

ultrahigh-energy CR and neutrino studies


Another JUBILEE
1934
P. A. Cherenkov, N. A. Dobrotin, I. M. Frank
ELBRUS


1934
P. A. Cherenkov
⇓
⇓Elbrus
Observation of air showers previously discovered by D. V. Skobeltsyn at sea level
The first mountain CR experiment in our country

ULTRAHIGH-ENERGY CR AND NEUTRINOS



- **What are the highest particle energies in nature?**
- **What their sources?**

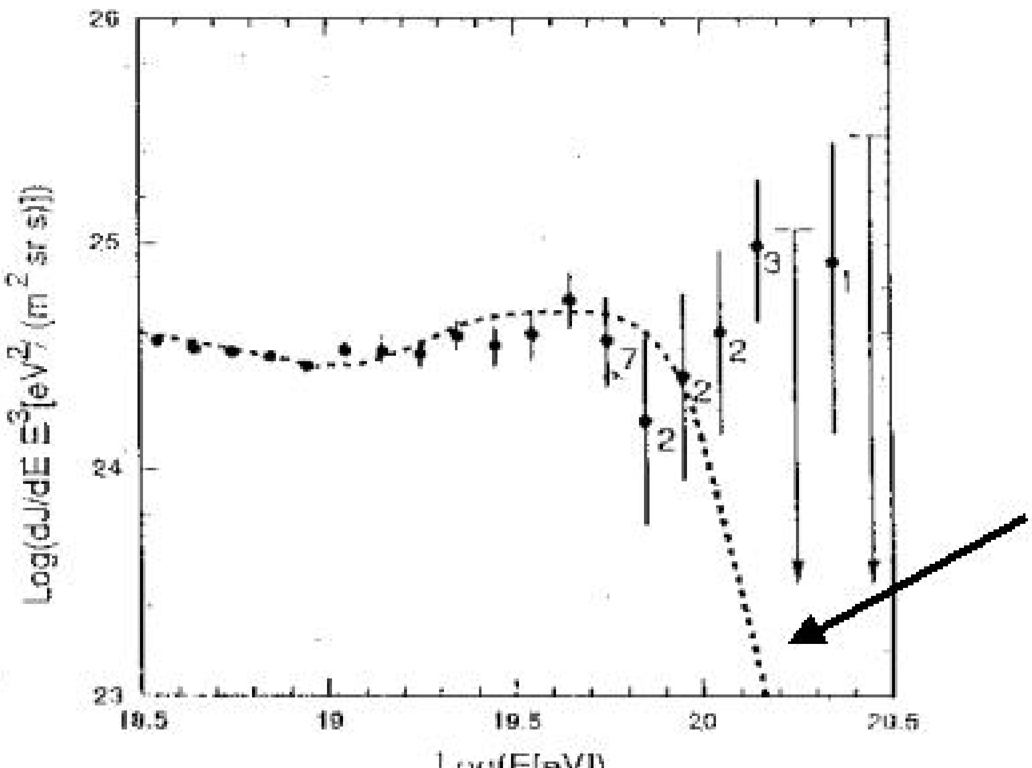
•Many generations of CR detectors

•To-date ~ 20 events with

$E \geq 10^{20}$ eV

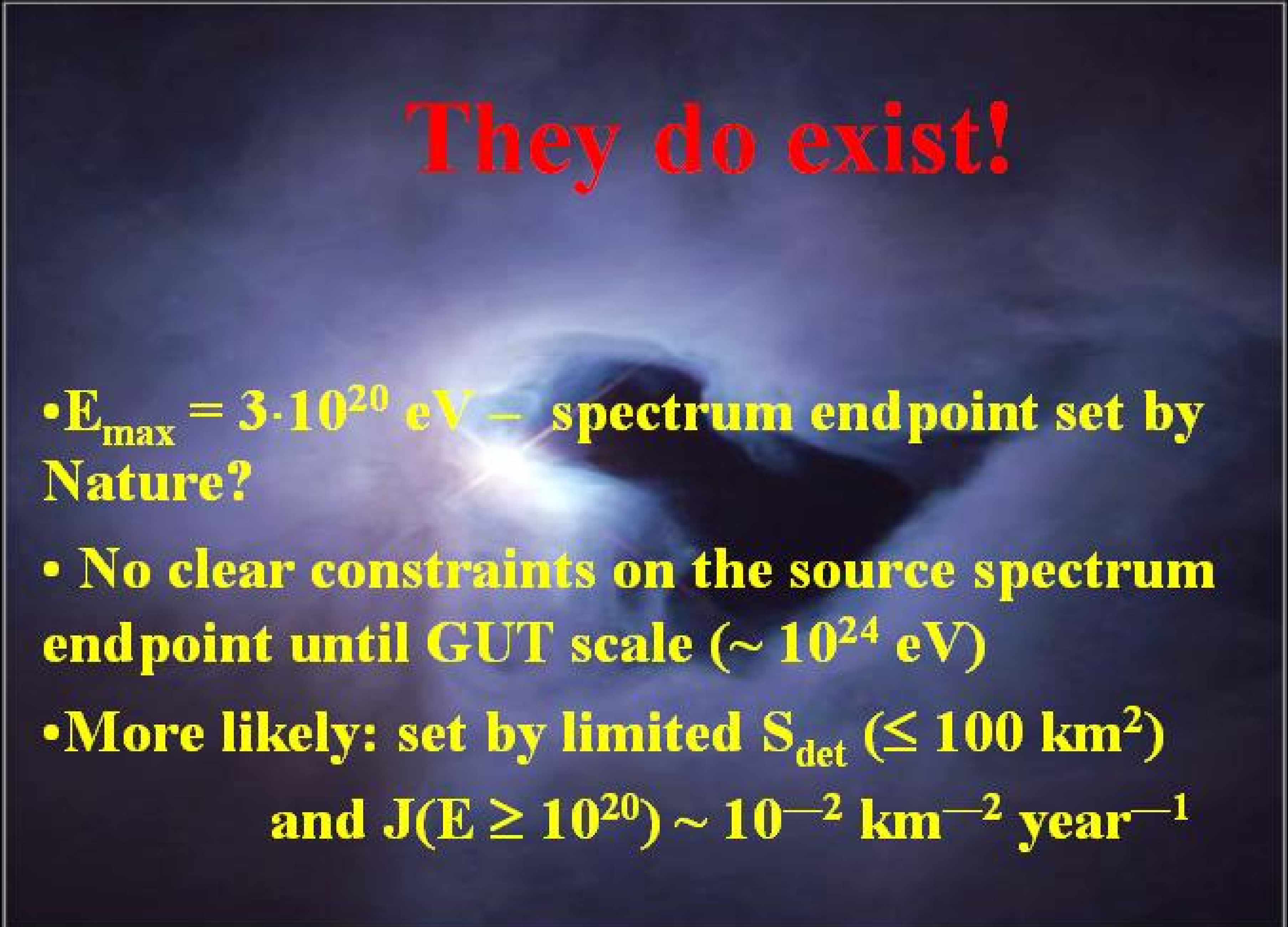
Nature? Sources?

“They should not exist”! ⇐ GZK cutoff



GZK cutoff

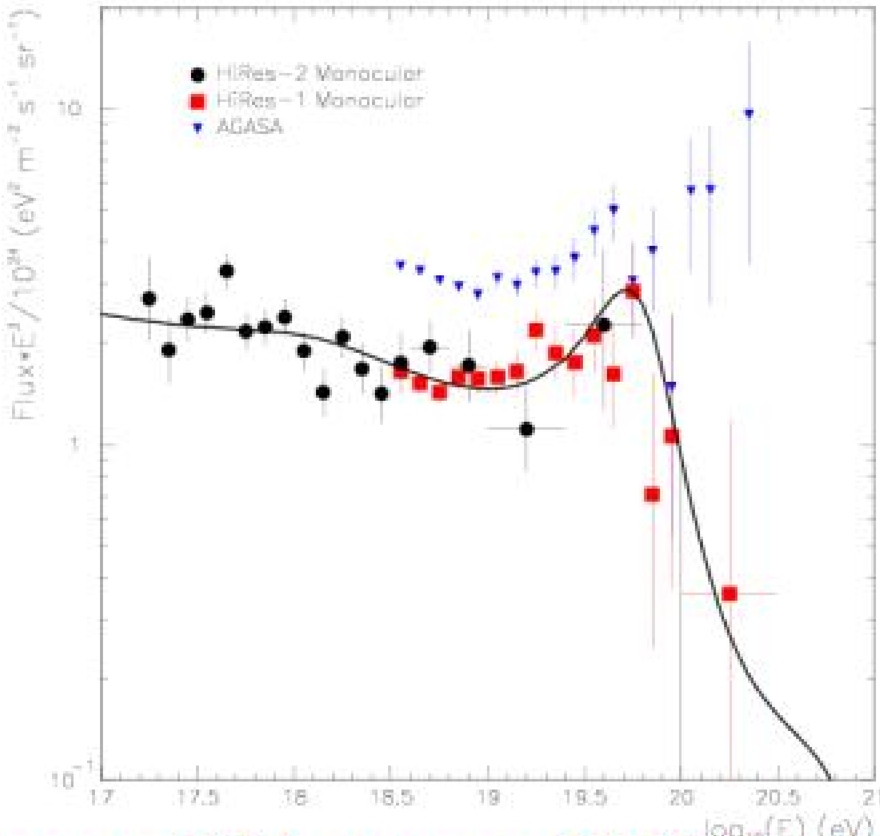
Reflection Nebula NGC 1999



They do exist!

- $E_{max} = 3 \cdot 10^{20}$ eV – spectrum endpoint set by Nature?
- No clear constraints on the source spectrum endpoint until GUT scale (~ 10^{24} eV)
- More likely: set by limited S_{det} ($\leq$ 100 km^2) and $J(E \geq 10^{20}) \sim 10^{-2}\ km^{-2}\ year^{-1}$

Preliminary data from HiRes



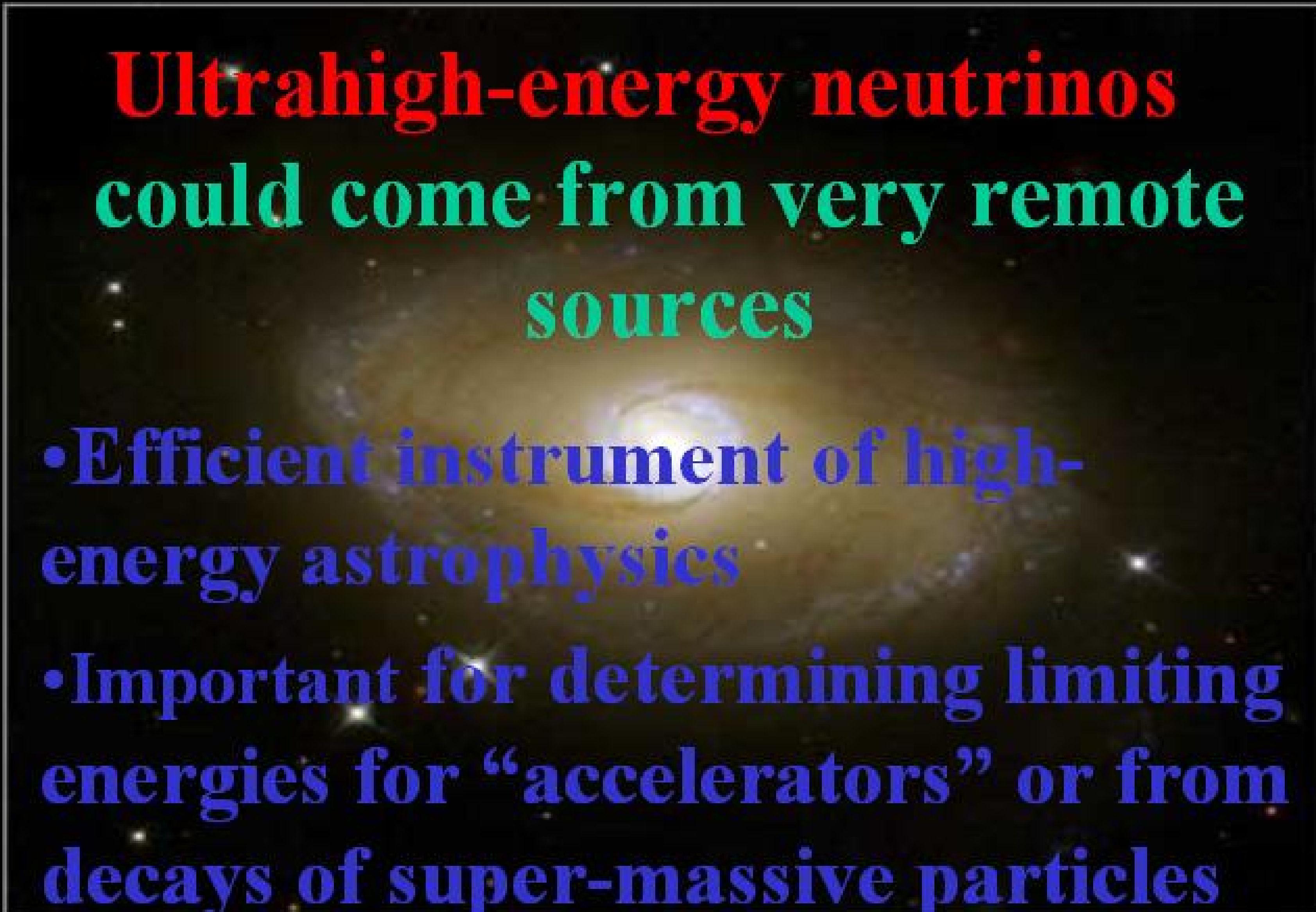
New data on CR near GZK are needed!

The M87 Jet

Elucidation of the UHECR nature - **fascinating physical/astrophysical findings, may be new physics**

- **Acceleration mechanism in superpower accelerators of the Universe**
- **Energy region – beyond reach of terrestrial accelerators – unique opportunity for studying particle physics at ultrahigh-energy scale**

Hubble Heritage



Ultrahigh-energy neutrinos could come from very remote sources

- Efficient instrument of high-energy astrophysics
- Important for determining limiting energies for "accelerators" or from decays of super-massive particles

The Dumbbell Nebula • M27

The main problem of both UHECR and UHEN event detection - rarity

- Standard GZK ν flux: < 1 / (km^2 day 2π sr)
- Interaction probability in 1 km of water ~ 0.2 %
- 1 km^3 detector – 1 GZK ν event every 2 years
- Detectors with huge apertures are required

For CR: $A_{eff} \geq 10^5$ km^2 sr. For ν: $V_{eff} >> 1$ km^3

- Traditional methods become inadequate
- The most promising –

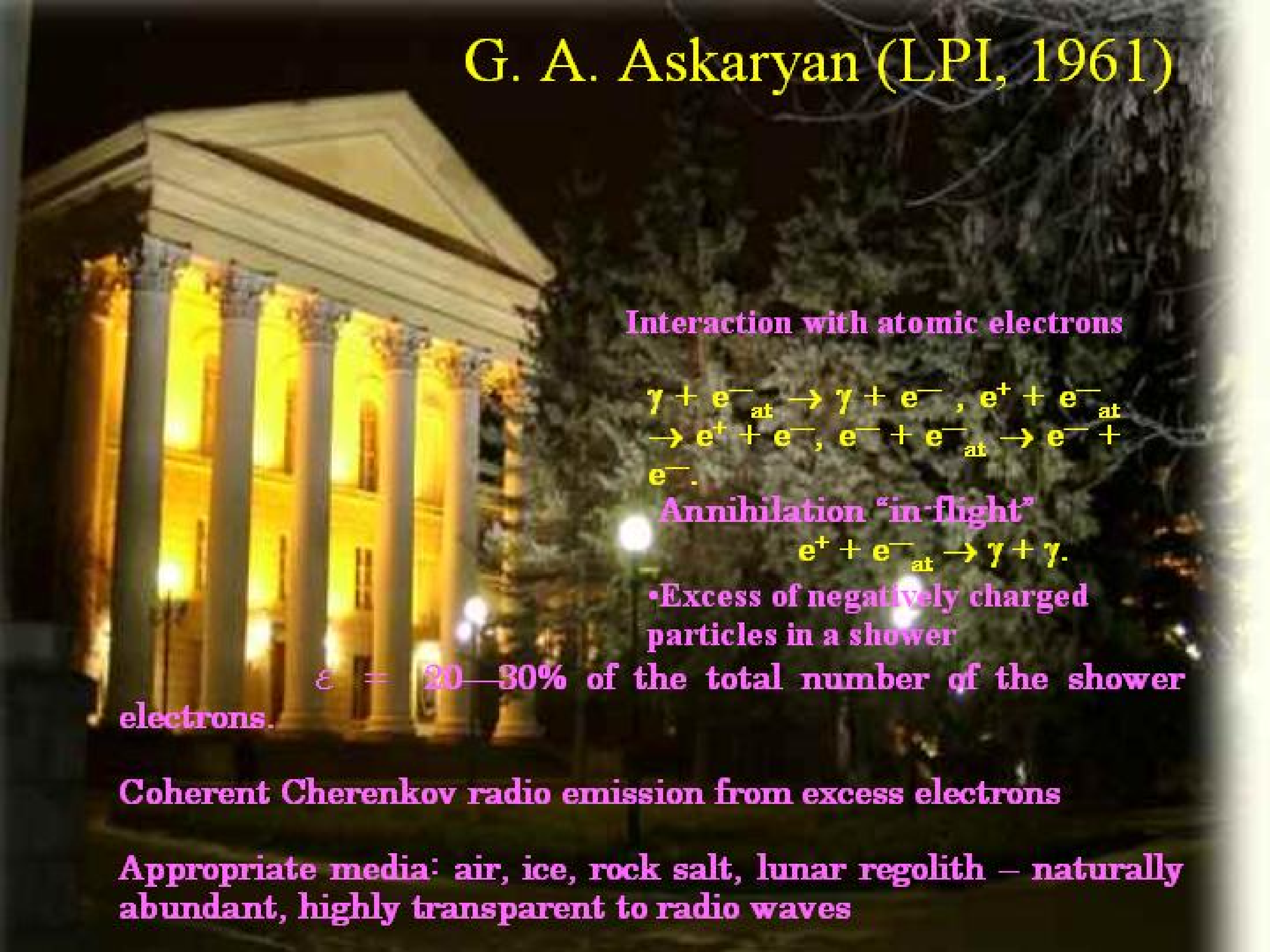
Coherent Cherenkov Radio Method

Hodge 301 in the Tarantula Nebula

Historical background

- Optical Cherenkov radiation from EAS was first observed by Jelley in 1953
- Extension to radio band?
- But:
- (a) f (and P) 5—8 orders of magnitude lower
- (b) destructive interference $\Rightarrow$ cancellation of contributions from e^+ and e^-

Hubble Heritage



G. A. Askaryan (LPI, 1961)

Interaction with atomic electrons

$\gamma + e^{-}_{at} \to \gamma + e^{-}$, $e^{+} + e^{-}_{at} \to e^{+} + e^{-}$, $e^{-} + e^{-}_{at} \to e^{-} + e^{-}$.

Annihilation “in-flight”

$$e^{+} + e^{-}_{at} \to \gamma + \gamma.$$

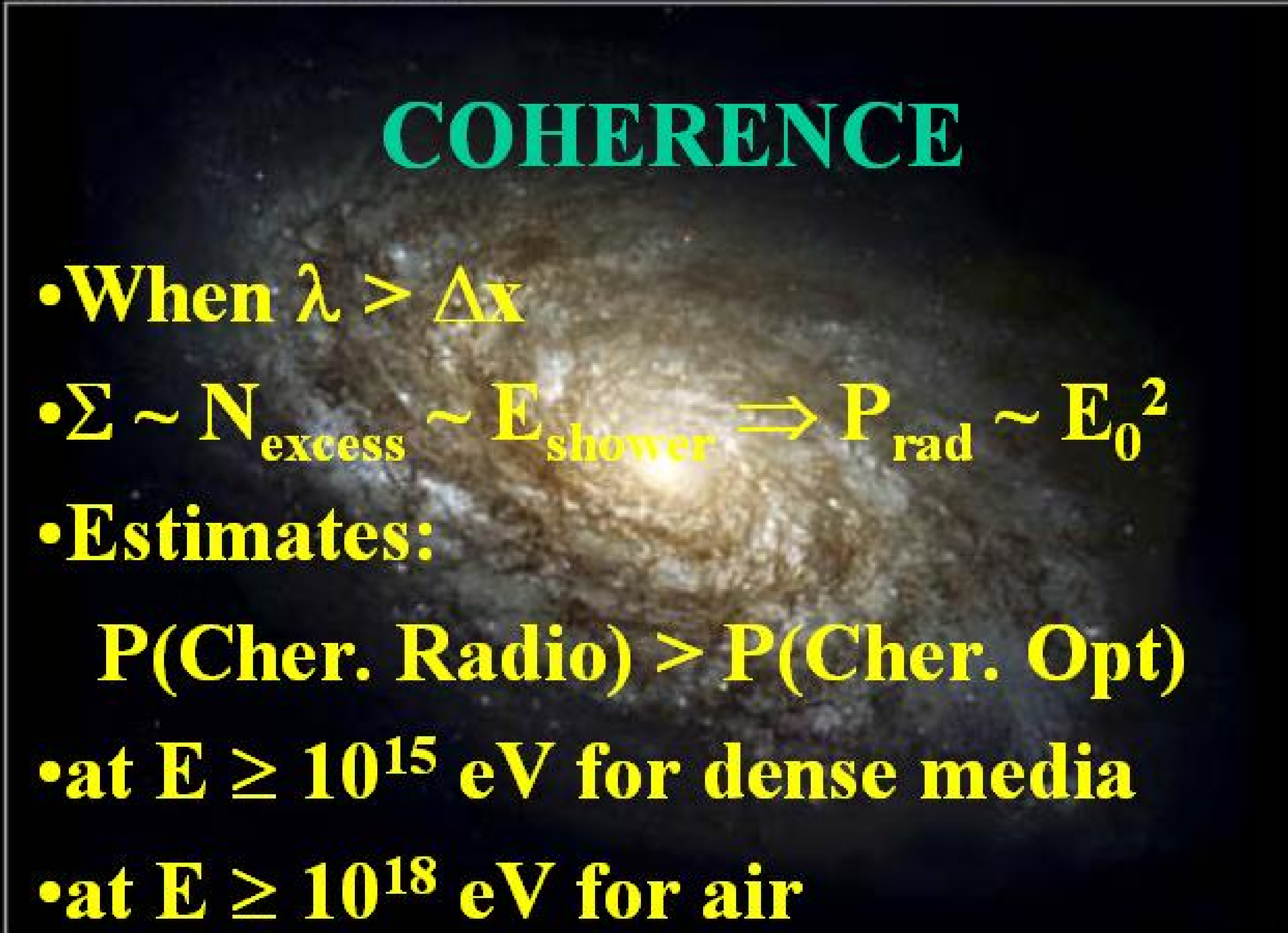
- Excess of negatively charged particles in a shower

ε = 20—30% of the total number of the shower electrons.

Coherent Cherenkov radio emission from excess electrons

Appropriate media: air, ice, rock salt, lunar regolith – naturally abundant, highly transparent to radio waves

Spiral Galaxy NGC 4414



COHERENCE

- When $\lambda > \Delta x$
- $\Sigma \sim N_{excess} \sim E_{shower} \Rightarrow P_{rad} \sim E_0^2$
- Estimates:

  P(Cher. Radio) > P(Cher. Opt)
- at $E \geq 10^{15}$ eV for dense media
- at $E \geq 10^{18}$ eV for air

Hubble Heritage

First experimental observations

- Radio signal from **EAS** – Jelley, 1965
- Later – many studies
- Radio signals from EAS were detected in coincidence with signals from shower array for f = 2 to 550 MHz
- In early 70th general interest in the **EAS** detection - concentrated on other methods

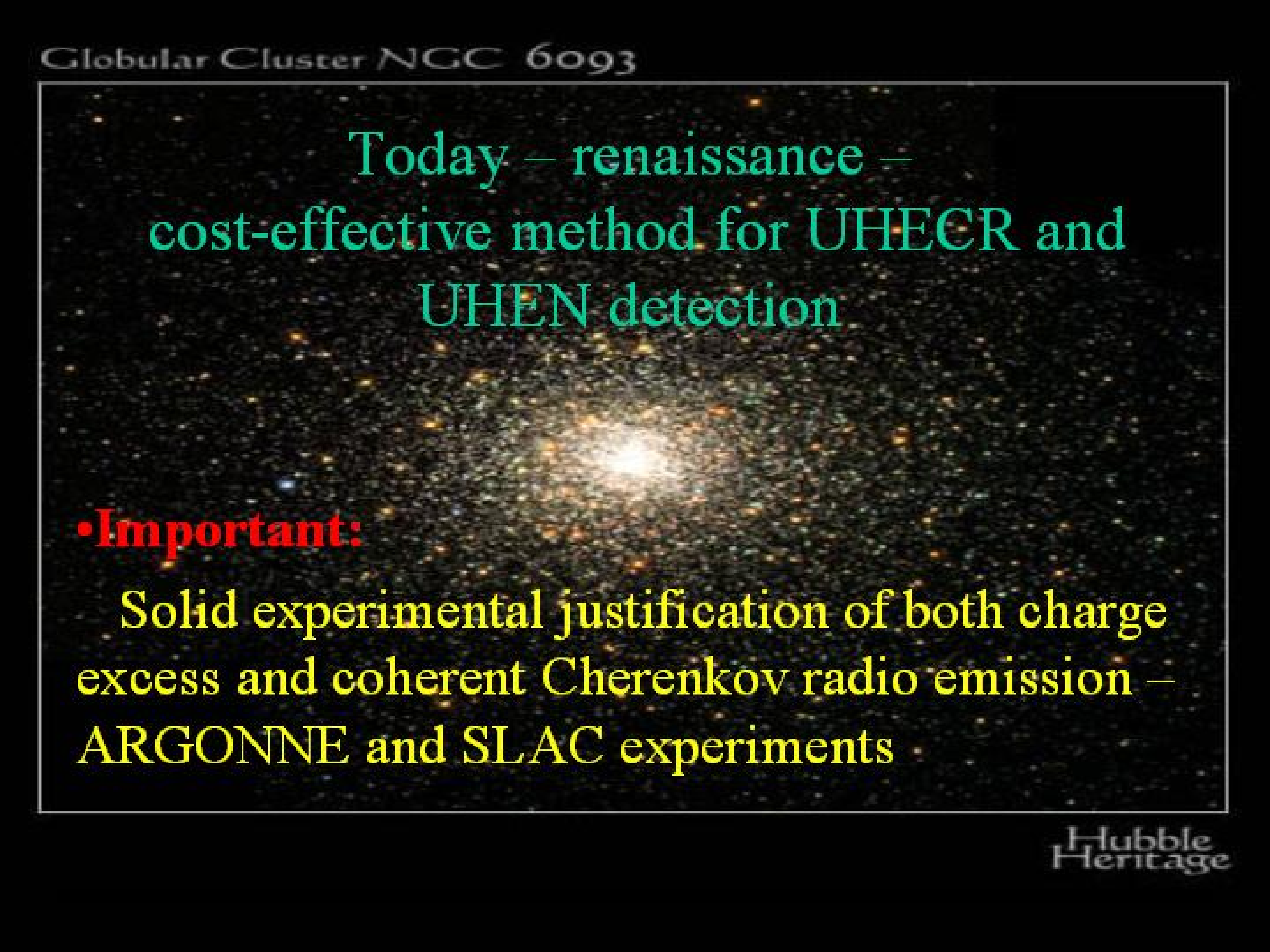
First proposals for dense media

- G. A. Gusev, M. A. Markov, I. M. Zheleznykh

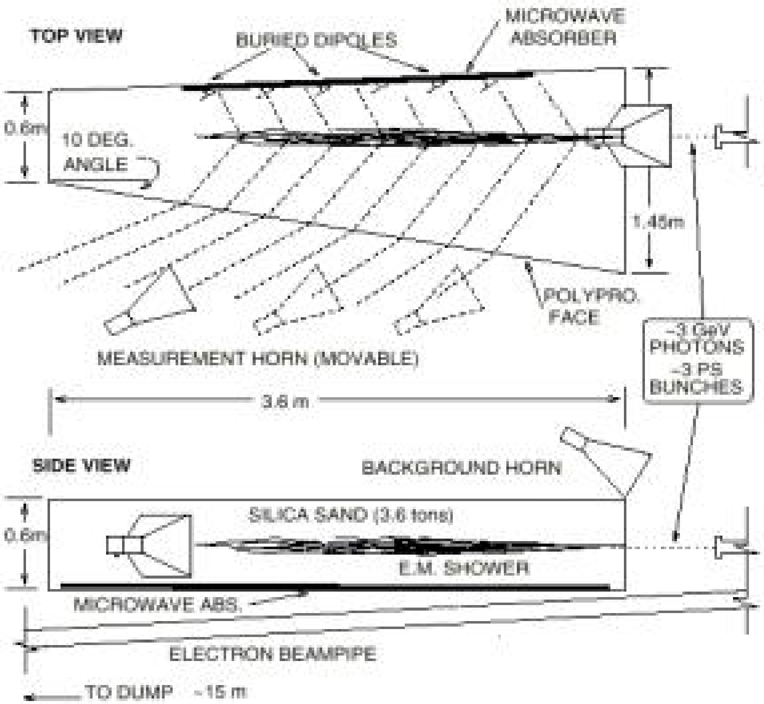
RAMAND (Radio Antarctic Muon and Neutrino Detector) **Antarctic ice**, 1983

- R. D. Dagkesamanskii, I. M. Zheleznykh

- RAMHAND (RAdio Moon Hadron and Neutrino Detector)- observation of the **Moon with terrestrial radio telescopes**, 1988


Globular Cluster NGC 6093
Today – renaissance –
cost-effective method for UHECR and
UHEN detection
•Important:
Solid experimental justification of both charge excess and coherent Cherenkov radio emission – ARGONNE and SLAC experiments
Hubble Heritage

Lunacee II target in SLAC Final Focus Test Beam area

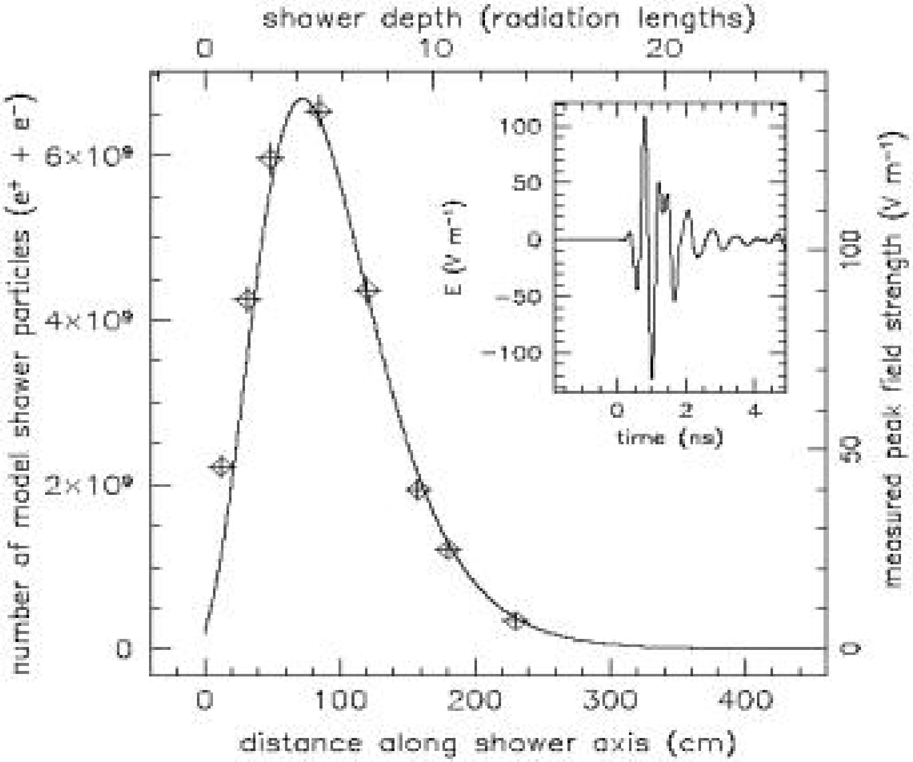


- Use 3.6 tons of silica sand, brem photons to avoid any charge entering target

  ==> no transition radiation

- Monitor all backgrounds carefully
  - but signals were much stronger!

Shower profile observed by radio (~2GHz)



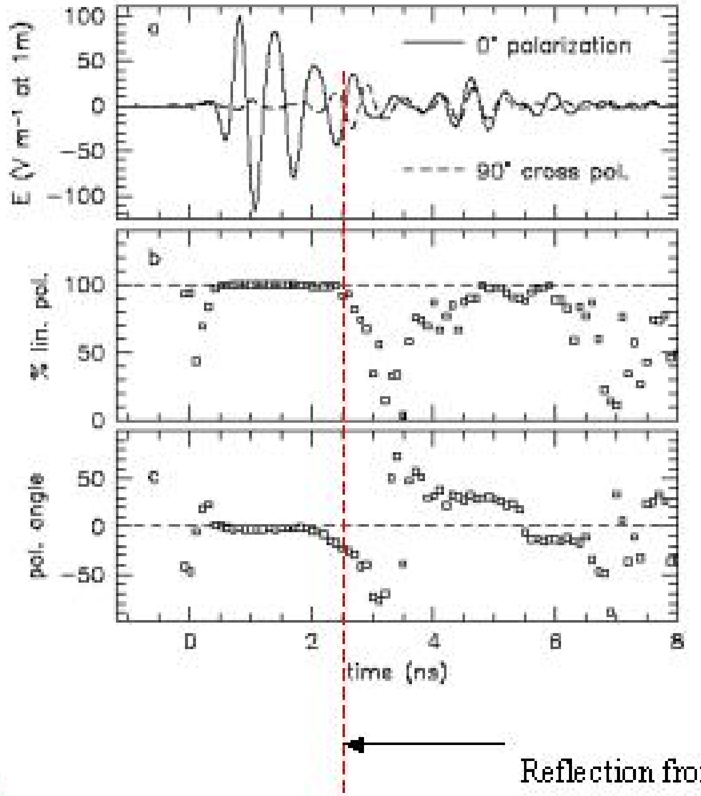
- Measured pulse field strengths follow shower profile very closely
- Charge excess also closely correlated to shower profile

Coherence of Cherenkov radio emission

POLARIZATION

Cherenkov radiation predictions:

- 100% linearly polarized
- plane of polarization aligned with plane containing Poynting vector **S** and particle/cascade velocity **U**



Reflection from side wall

- Observed:
  - 100% linearly polarized pulses
  - Plane of polarization exactly aligned with plane of **S** and **U**

Coherence and absolute field strength

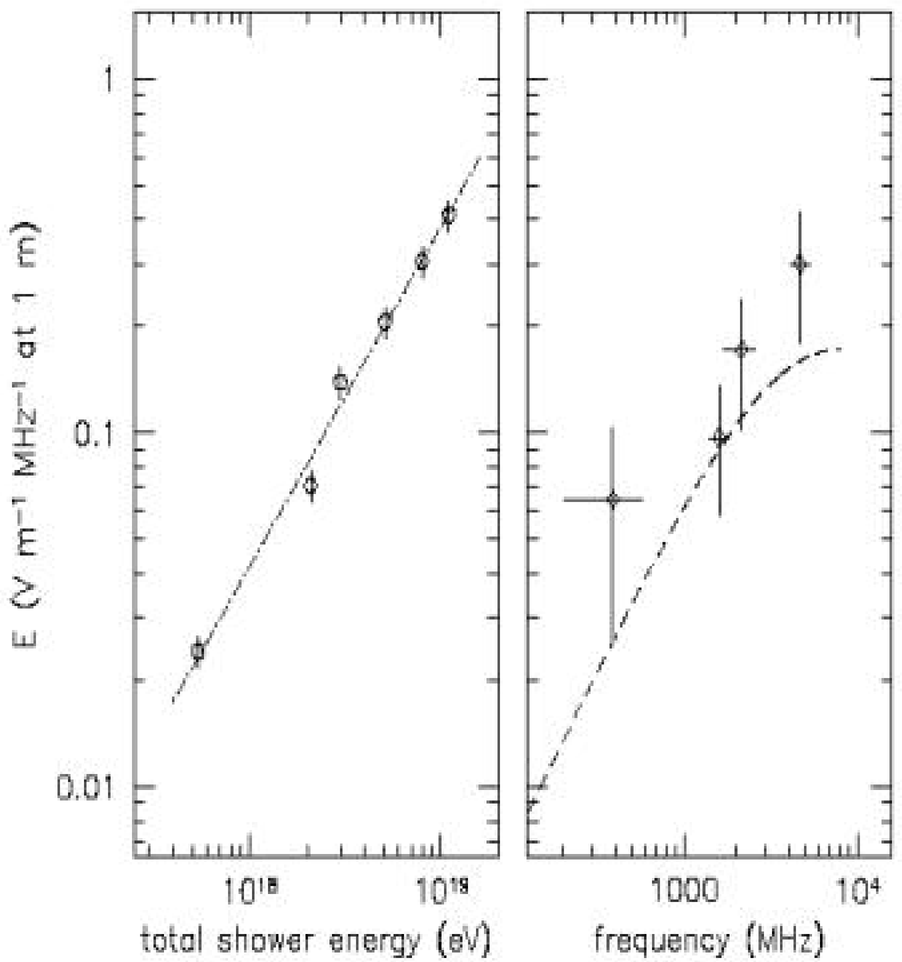
- **No departures from coherence**
  - **field strength ~ Nγ ~ shower energy**

- **Frequency dependence also as expected for coherent Cherenkov:**
  E ~ ν dν up to ~2GHz

All observed characteristics are consistent with coherent Cherenkov radiation

$E_{bunch} \sim 10^{19}$ eV

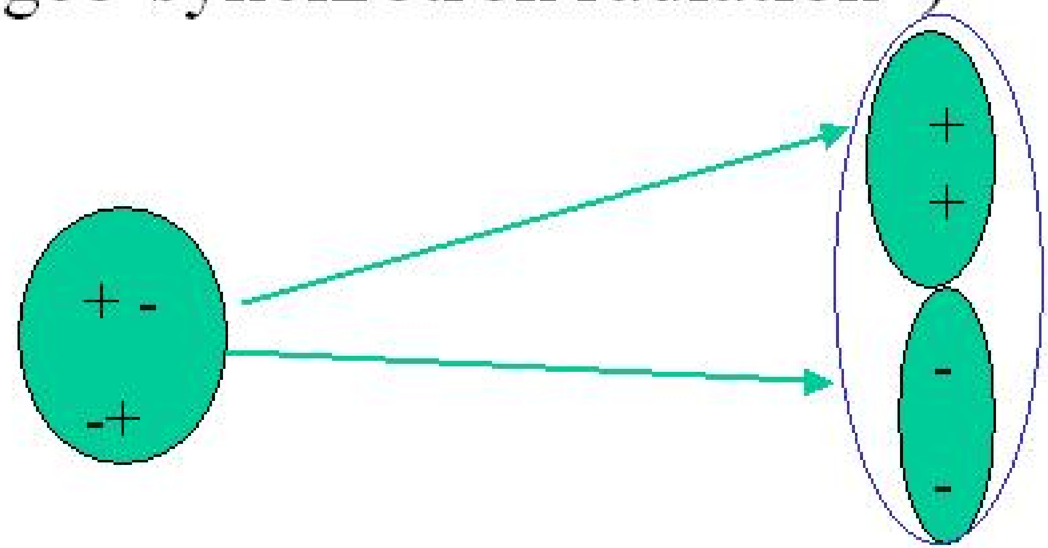
Imitation of radio emission from UHE cascade



For air showers – some other mechanisms

- The most important –

Geomagnetic charge separation (electric dipole + transverse current) V. I. Goldanskii, LPI, 1961 ("geo-synchrotron radiation")



Peculiarities of Cherenkov radio emission

- **Optical:** $\lambda << \xi\ (l, \Delta x, L_{show})$
- **Radio:** $\lambda \sim$ or $> \xi$
- **Important: interference, coherence, cascade space-time structure**
- **MC modeling of UHE shower development**
- **"Macroscopic" – model for shower current**
- **"Microscopic" – summing of contributions from all particle tracks**

Cherenkov radiation in dense medium (ice)

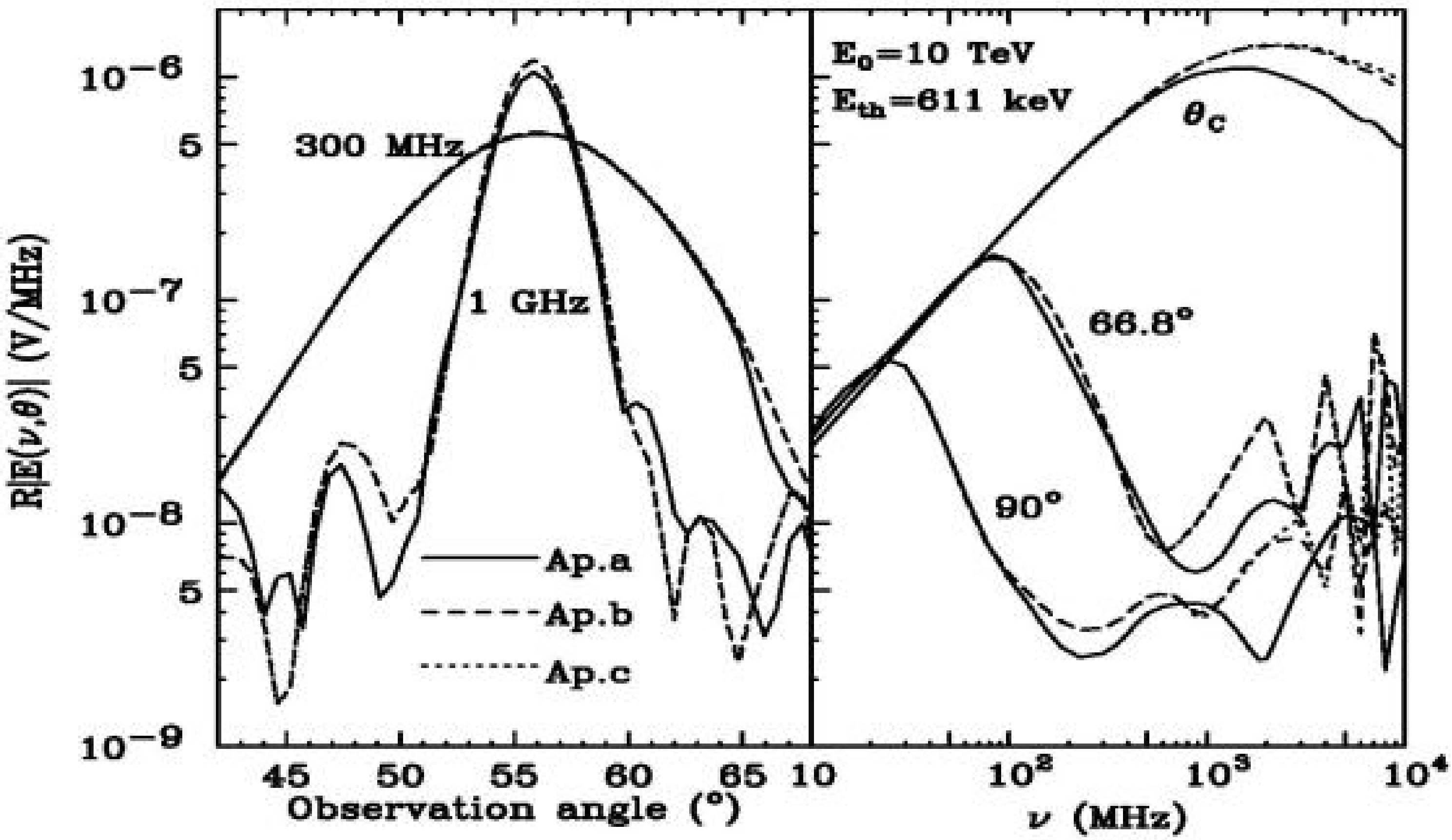
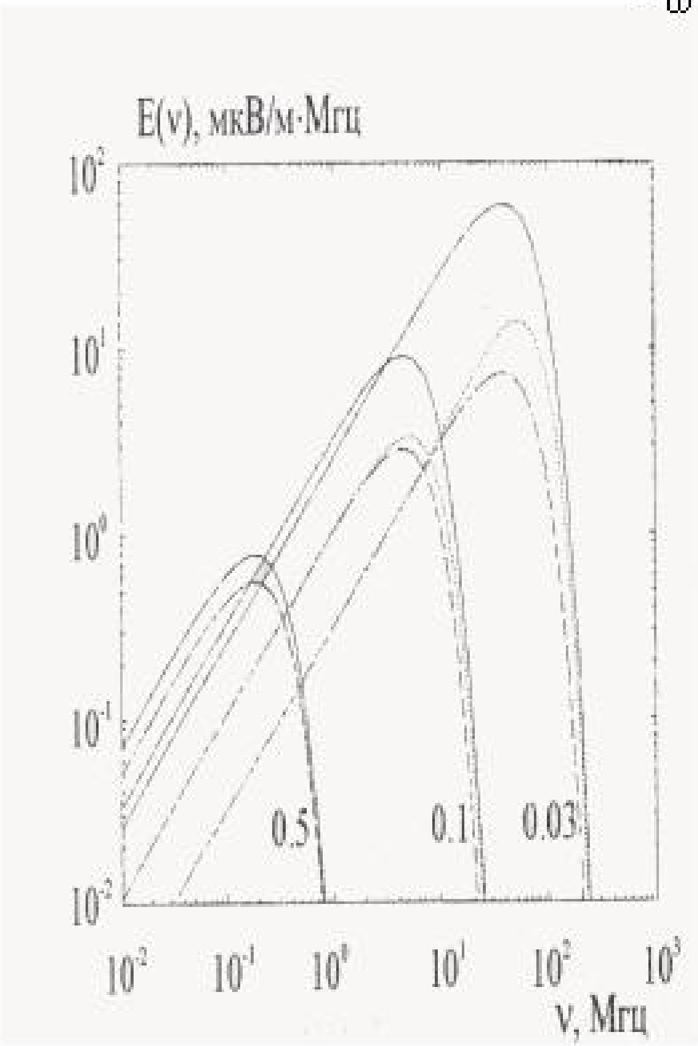


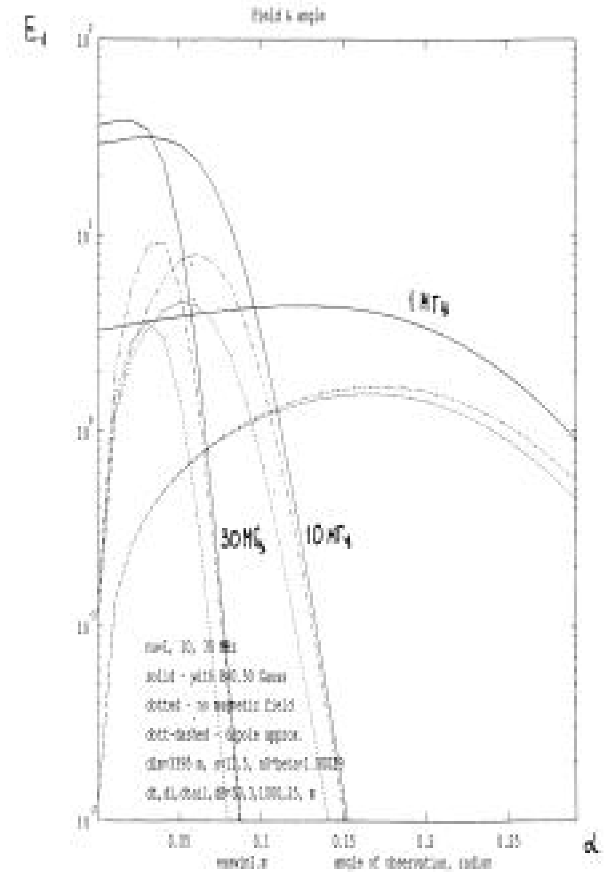
FIG. 8. Results of the full simulations with different algorithms for track subdivisions in the calculation of the electric field amplitudes as discussed in the text (appendix A). Shown are both the angular distributions for 300 MHz and 1 GHz and the frequency spectrum at three different observation angles for a 10 TeV electron shower with a threshold of 611 keV.

Cherenkov radiation in the normal atmosphere

$E_\omega(\mu V/m\ MHz)$



f (MHz)



Radiation angle α

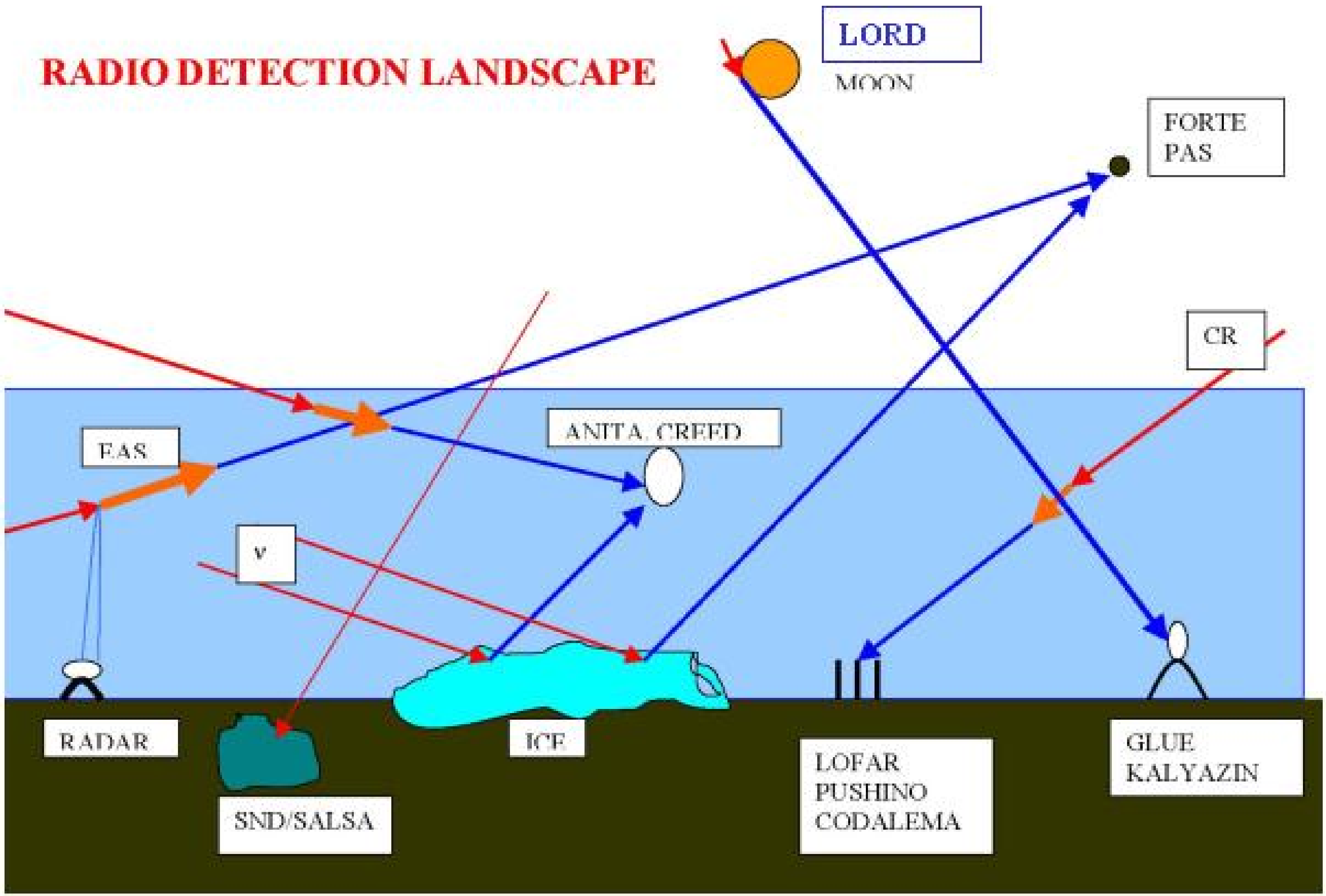
Planetary Nebula NGC 6751

Summary: merits of radio method

- Long propagation length of radio waves ⇒ scanning of large target volumes ($\sim 10^3 \times V_{opt}$)
- Calorimetric energy measurements
- Higher duty cycle
- Additional information on shower development
- Quadratic rise with initial particle energy
- Well established radio technique
- Experimentally demonstrated

Hubble Heritage

Current initiatives on UHECR and UHEN radio detection



CURRENT INITIATIVES IN RADIO DETECTION

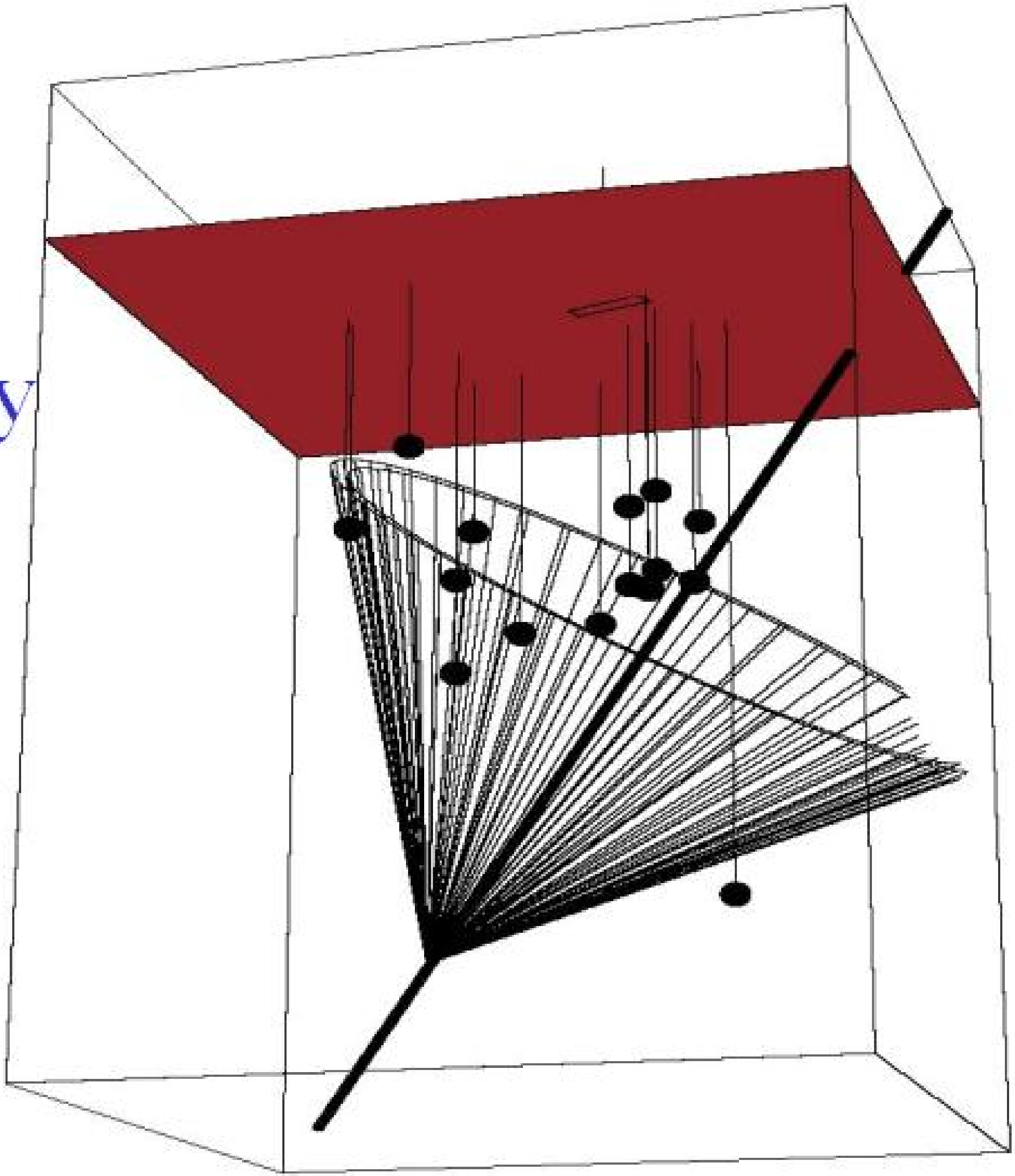
- **Ice**: RICE - ongoing, started in 1996
- FORTE, was active in 1997—1999
- ANITA – proposal (2001)
- CREED – proposal (2003)
- **Salt**: SALSA – proposal (testbed)
- SND – proposal (testbed)
- **Moon**: KALYAZIN (suspended)
- GLUE – ongoing, started in 1998
- LORD – proposal (2004)
- **EAS**: PUSHINO, CASA-MIA, CODALEMA, LOFAR

ICE

- **RICE** (Radio Ice Cherenkov Detector)
- **Antarctic icecap - 20-channel dipole array**
- $V \sim (200\ m)^3$
- H = 100—300 m (“AMANDA holes”);
- $V_{eff} \sim 25\ km^3 sr$ (10^{16} eV)
- Frequencies: 200 MHz—1 GHz
- **Started in 1996**

RICE

geometry

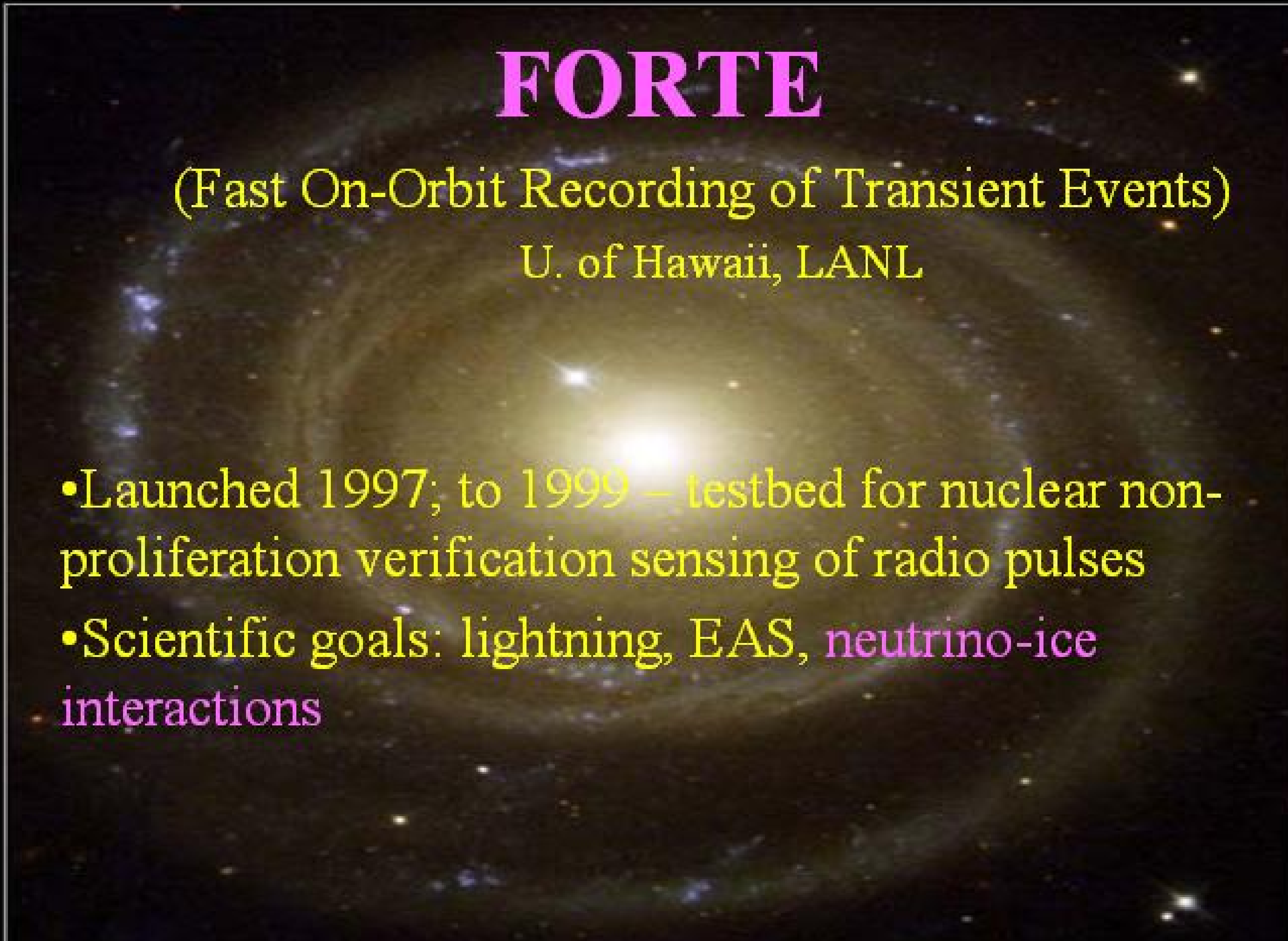


FORTE

(Fast On-Orbit Recording of Transient Events)

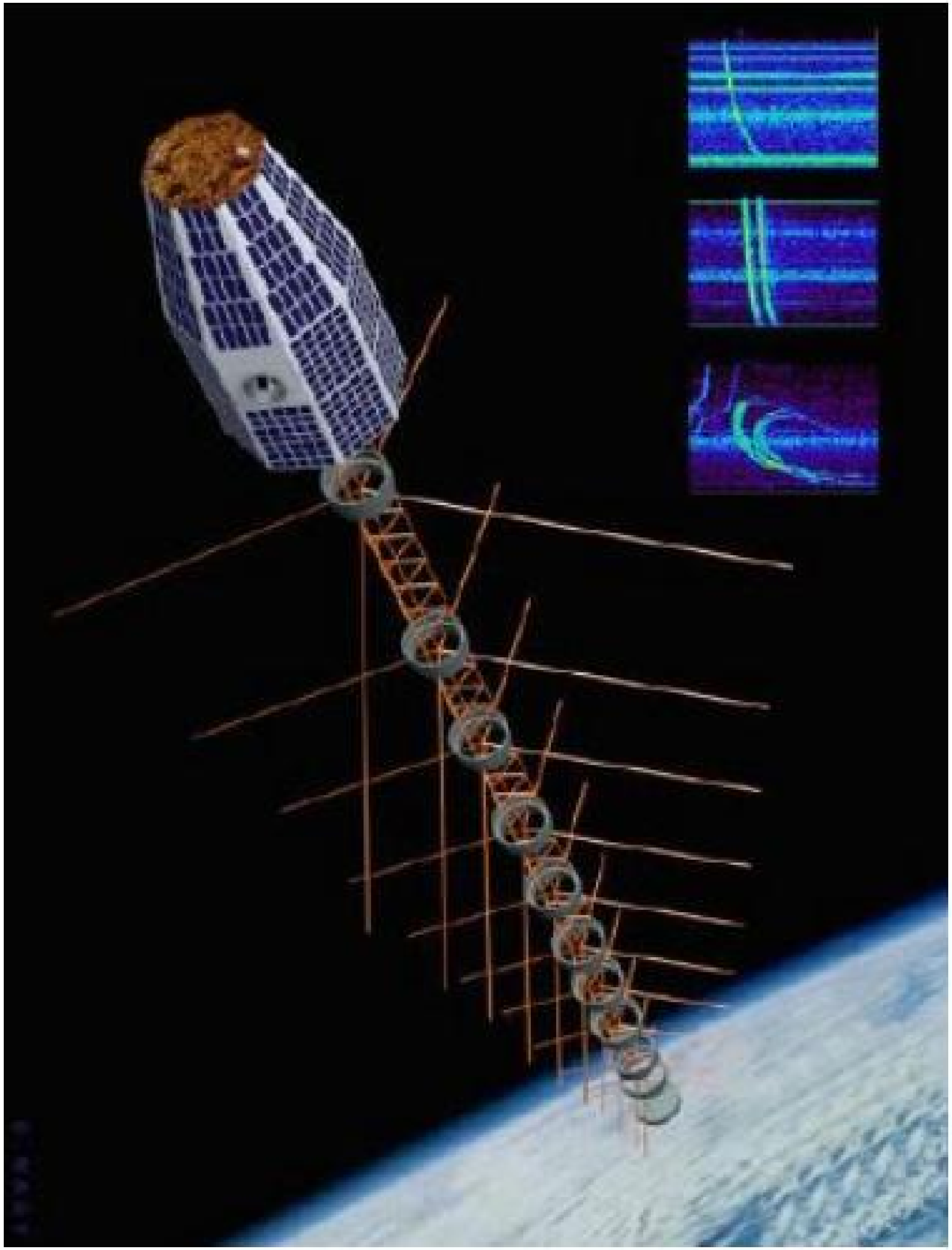
U. of Hawaii, LANL

- Launched 1997; to 1999 – testbed for nuclear non-proliferation verification sensing of radio pulses
- Scientific goals: lightning, EAS, neutrino-ice interactions



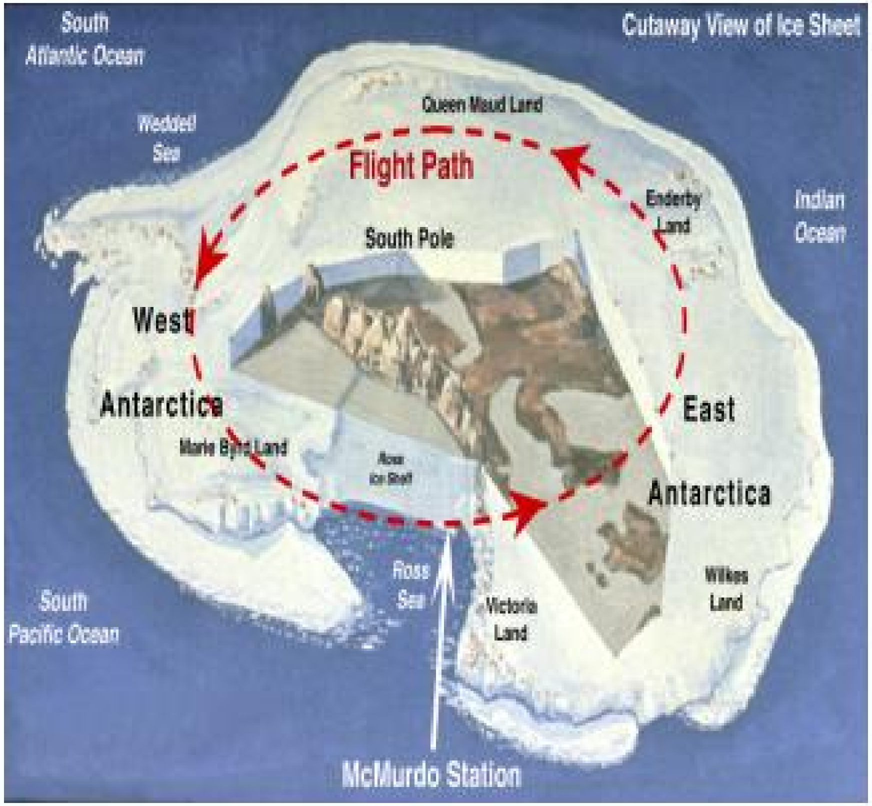
FORTE

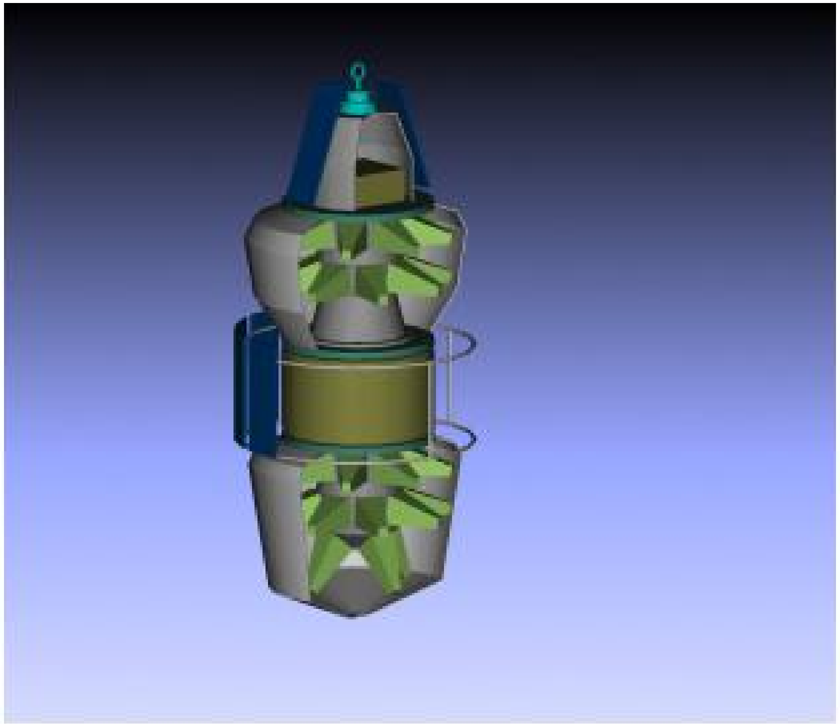
- H = 800 km, 70^0 inclination, circular orbit
- 2 orthogonal log-periodic dipole antennas
- 2 receivers, Δf = 22 MHz, f_{centr} = 20—300 MHz
- Optical Lightning System
- 8 trigger sub-bands (Δf = 2.5 MHz; δf = 1 MHz)
- First scientific goal: search for ν-induced events in Greenland ice sheet, $S \sim 1.8 \cdot 10^6$ km^2, h < 3 km (< 1 km for RF)



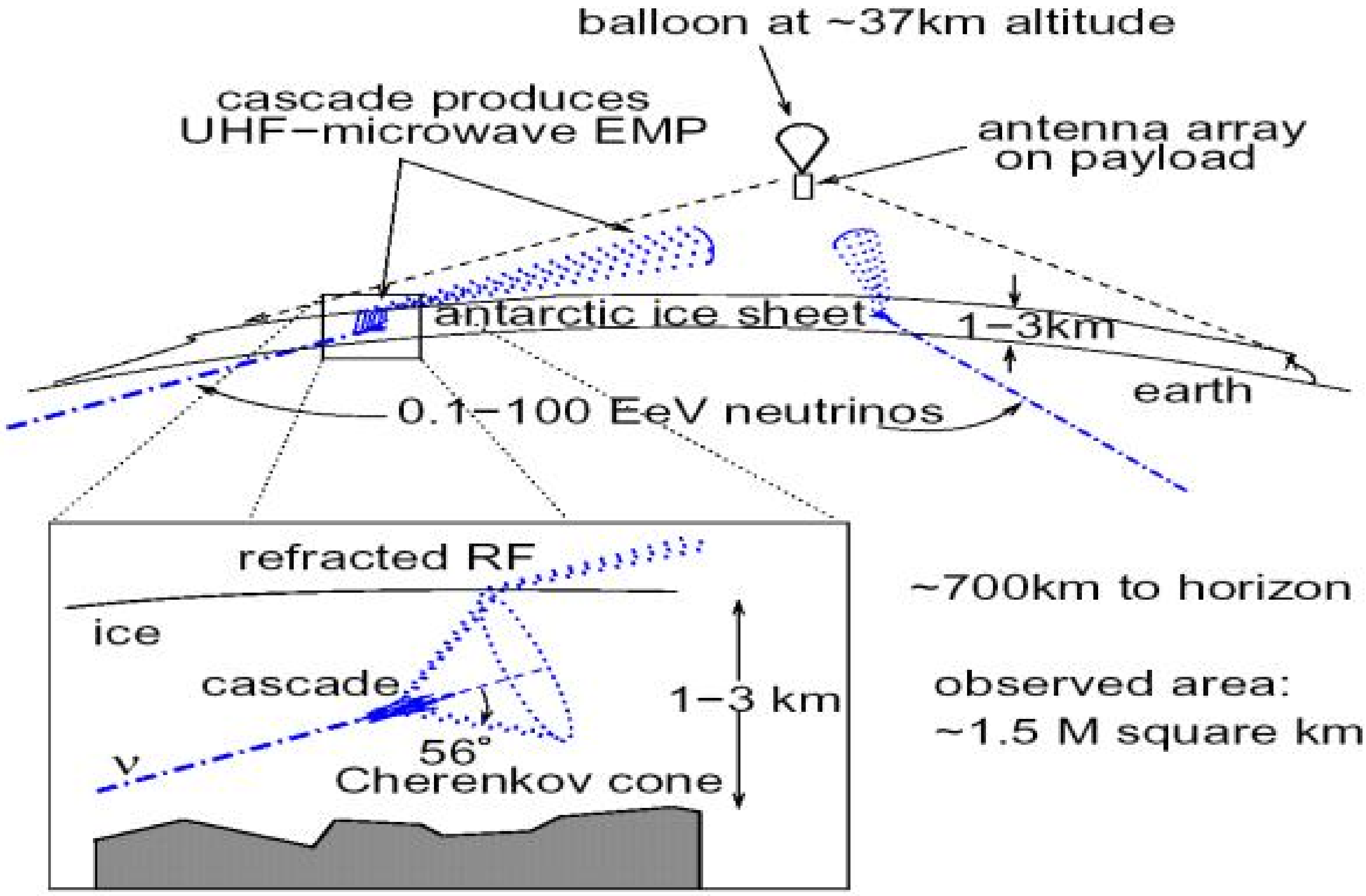
ANITA

Antarctic Impulsive Transient Antennas

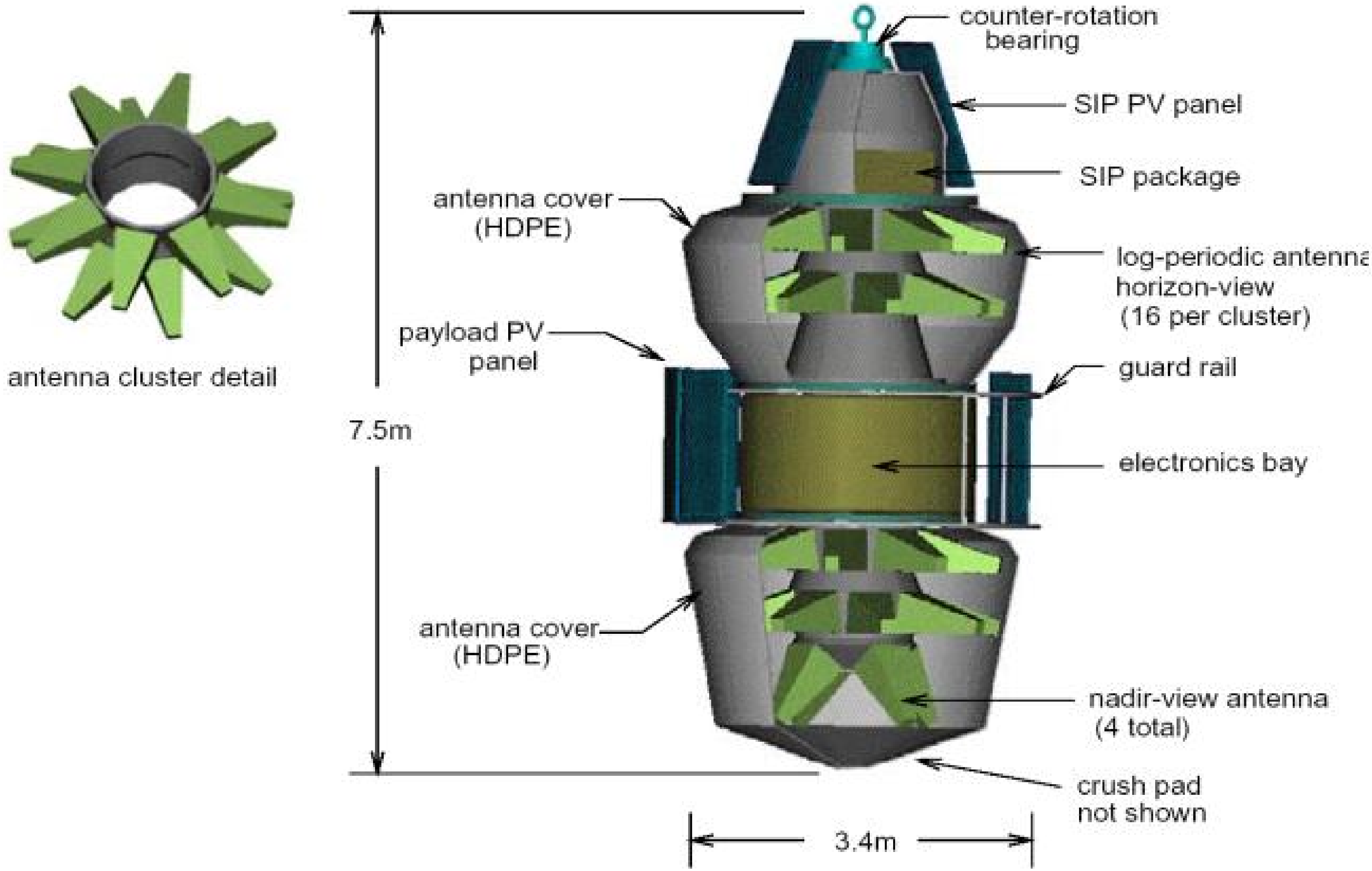




ANITA concept

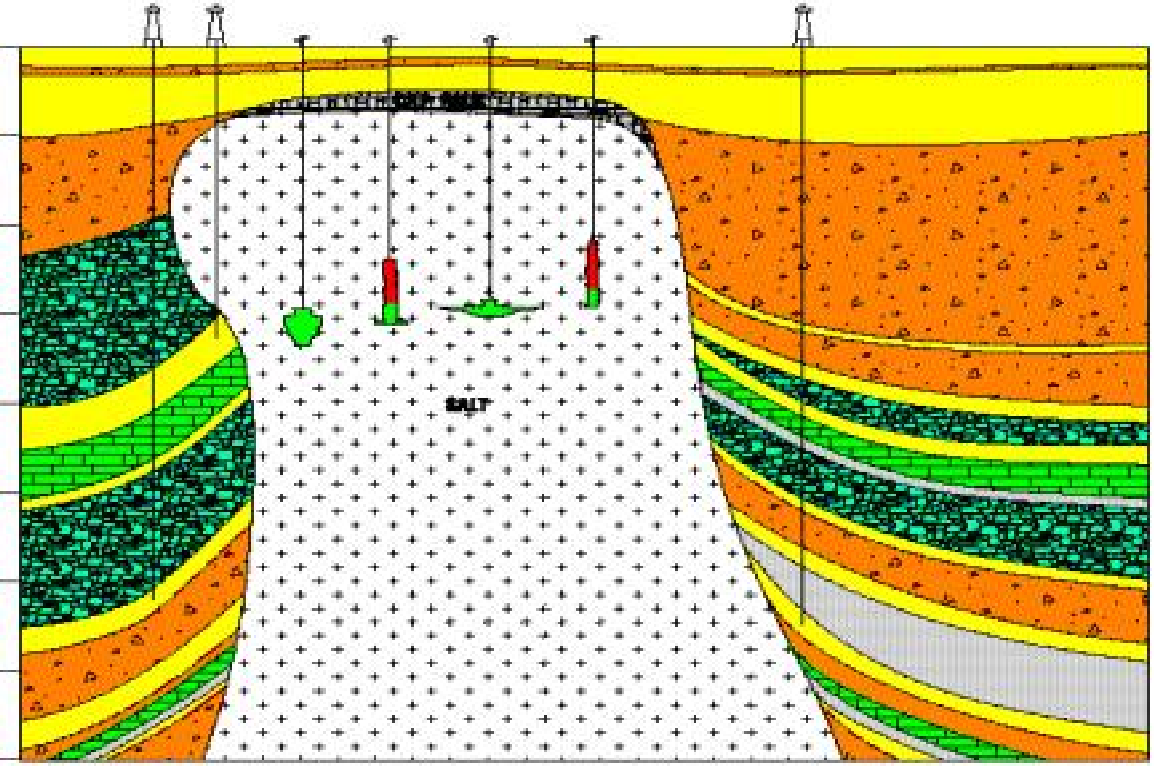


ANITA Payload



Natural salt domes

- Abundant in nature
- V ~ tens of km^3
- Radio-transparent
- Natural salt can be as clear as very cold ice, 2.4 times as dense;



SALSA

(SALtbed Shower Array) UCLA, Kansas U., Hawaii U., SLAC


- *In situ* **measurements in Hockley mine (Houston)**
- **h_{min} ~ 300 m,**
- **h_{max} ~ 10 km, V ~ 80 km³ (~ ×2.2 w.e.)**
- **Results: $\Lambda(f) \sim 300$ m $(f / 300\ \text{MHz})^{-1}$**
- **No polarization rotation or dispersion**
- **Low external noise (upper rock layer)**
- **Goal – 100 km³ neutrino radio detector**

SND project

(Salt Neutrino Detector)

- Tokyo Metropolitan University group
- Laboratory measurements of salt and limestone from Hallstadt mine (Austria), Asse Salt mine (Germany), Kamaishi (Japan), Jura (France)
- Detector array proposal

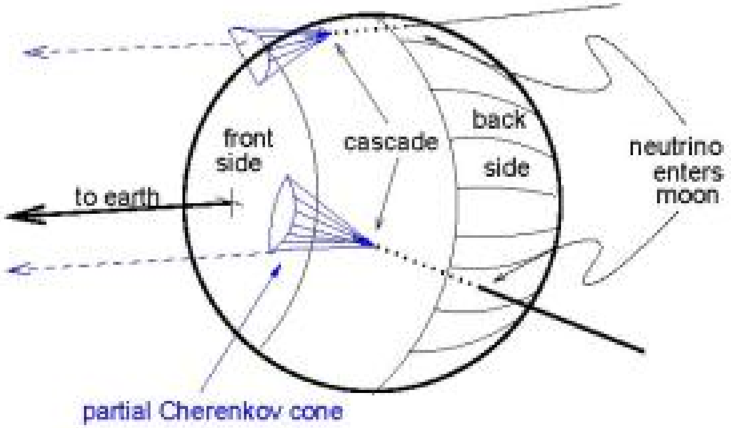
The feasibility of constructing UHEN detectors is confirmed

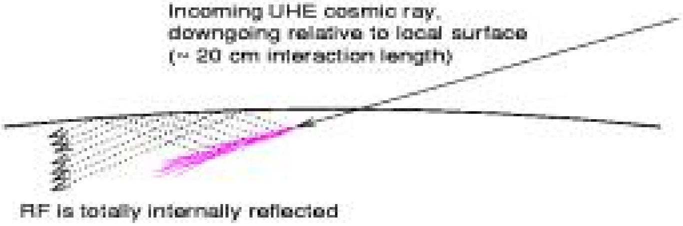
Moon as a target for CR and neutrinos

- R_{moon} = 1760 km,
- Regolith:

  aggregate of fine particles & small rocks ejected from lunar surface by meteorites;
- Mostly silicates, 10—20 m depth,
- $\Lambda \sim 20$ m / f (GHz); $\rho \approx 1.7$ g / cm^3
- $V_{eff} \sim 2\cdot10^5$ (km.w.e.)^3;

Detection geometry





"KALYAZIN"

Lebedev Physical Institute, INR

- Started in 1991
- 64-m OKB MEI radio telescope
- 5 dual-channel receivers:
- 0.6; 1.4; 2.3; 8.3 GHz
- Now - suspended

FIGURE 1. Kalyazin 64-meter radiotelescope.

Polar-Ring Galaxy NGC 4650A

GLUE

(Goldstone Lunar Ultra-High Energy Neutrino Experiment)

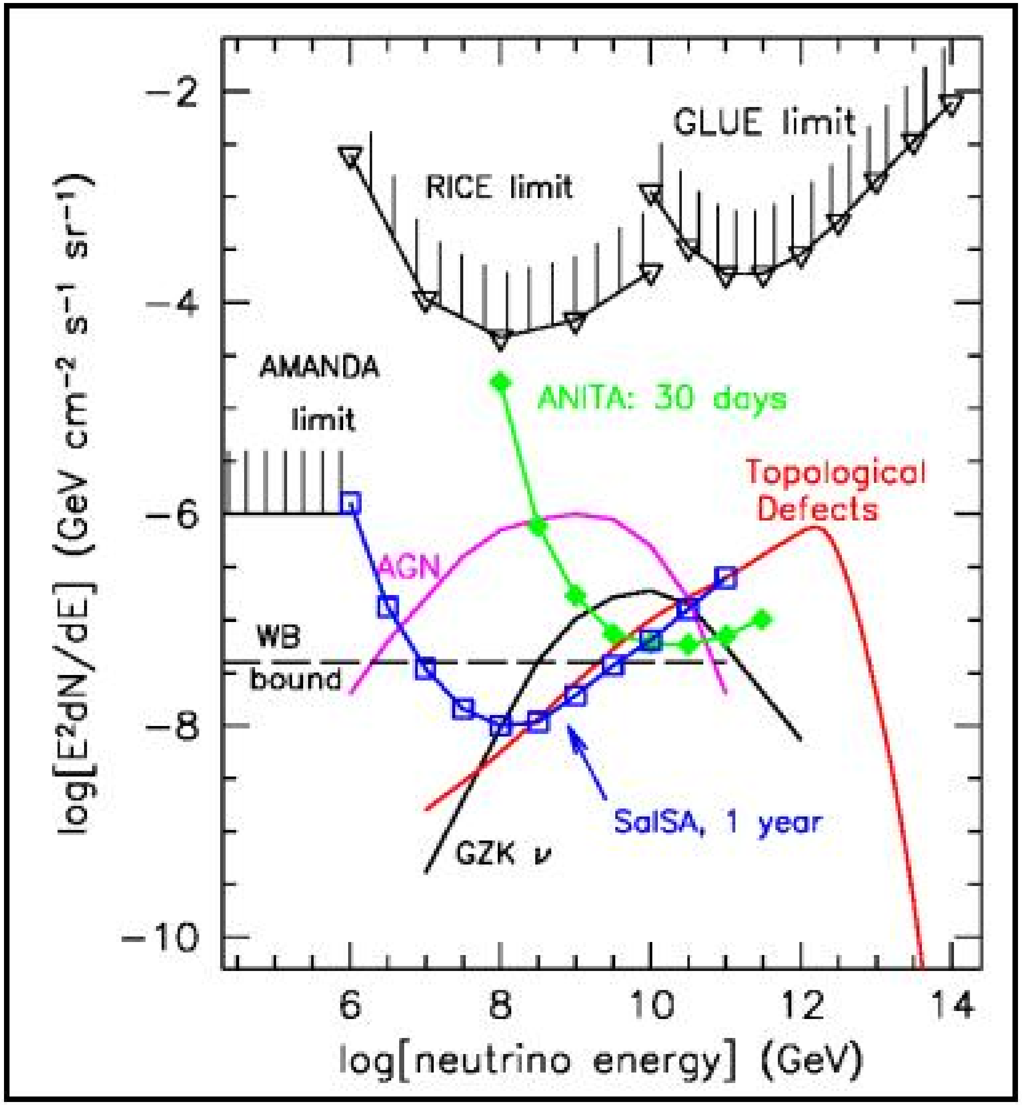
U. of Hawaii, JPL, UCLA

•From 1998 GLUE – Goldstone Deep Space Communication Antennas (NASA): two 34 m + 70 m radio telescopes, separation 22 km.

Hubble Heritage

Measured & Predicted Radio Limits

in comparison with some models for neutrino fluxes



- Radio is very competitive with the biggest proposed "traditional" neutrino telescopes at E>1—100 PeV

From P. Gorham, Aspen, 2002

LORD

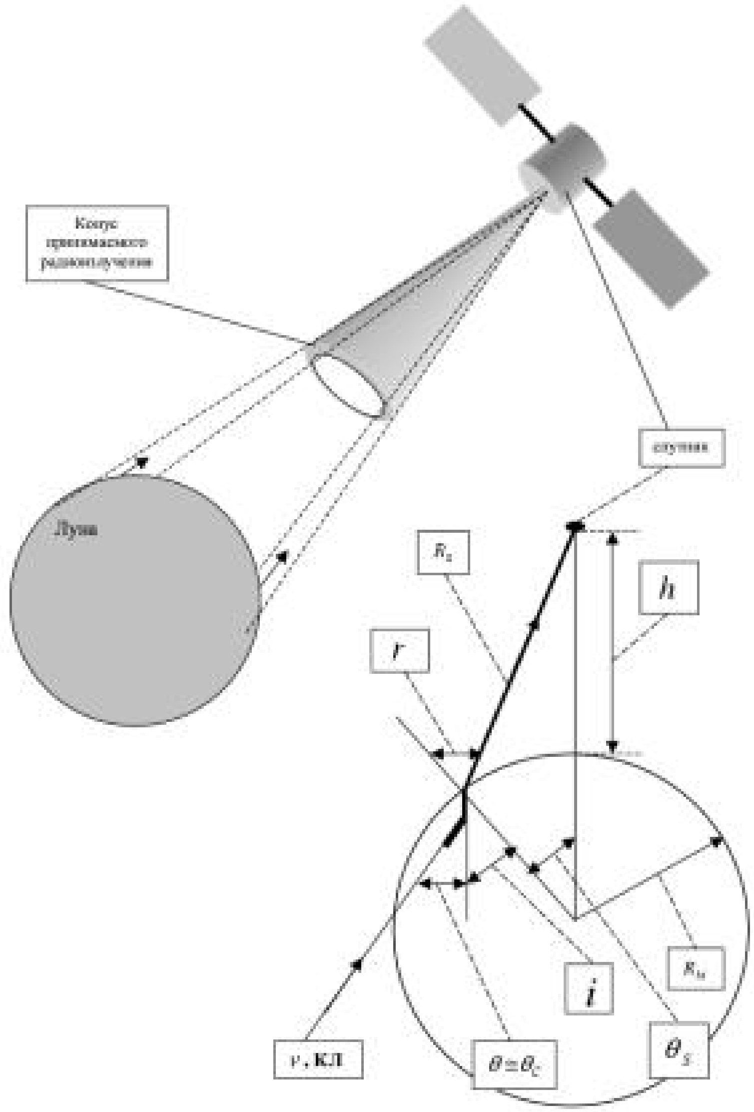
Lunar Orbital Radio Detector

- **Huge target mass $V_{eff} \sim 10^5$ (km.w.e.)^3**

Lunar satellite:

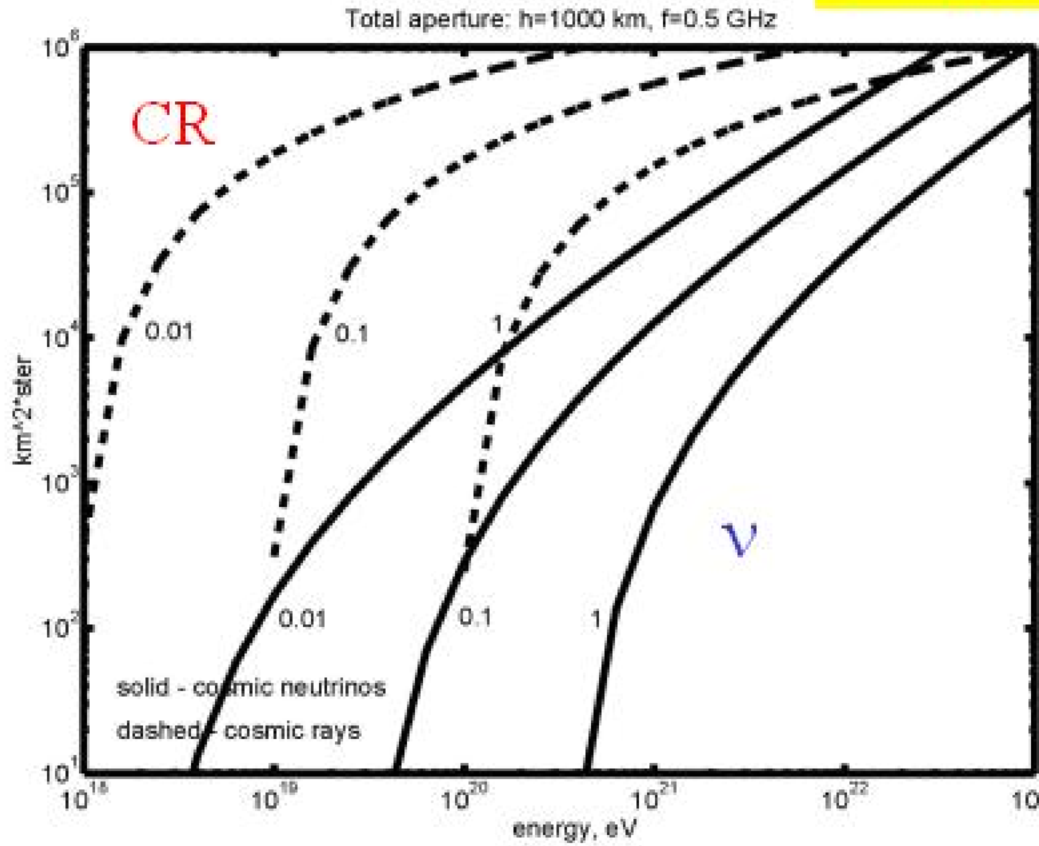
- **Very favorable background conditions**
- **Short (and variable) distance – high signal**

Moon

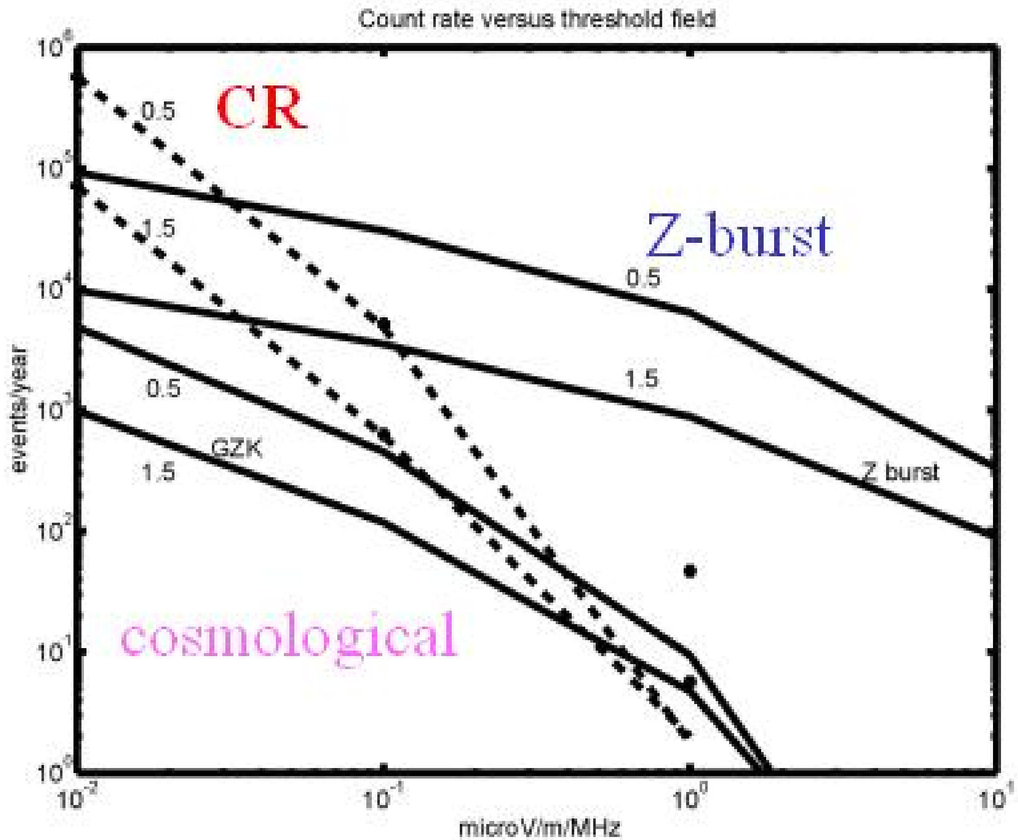


Geometry of the LORD experiment

$10^6\ km^2sr$

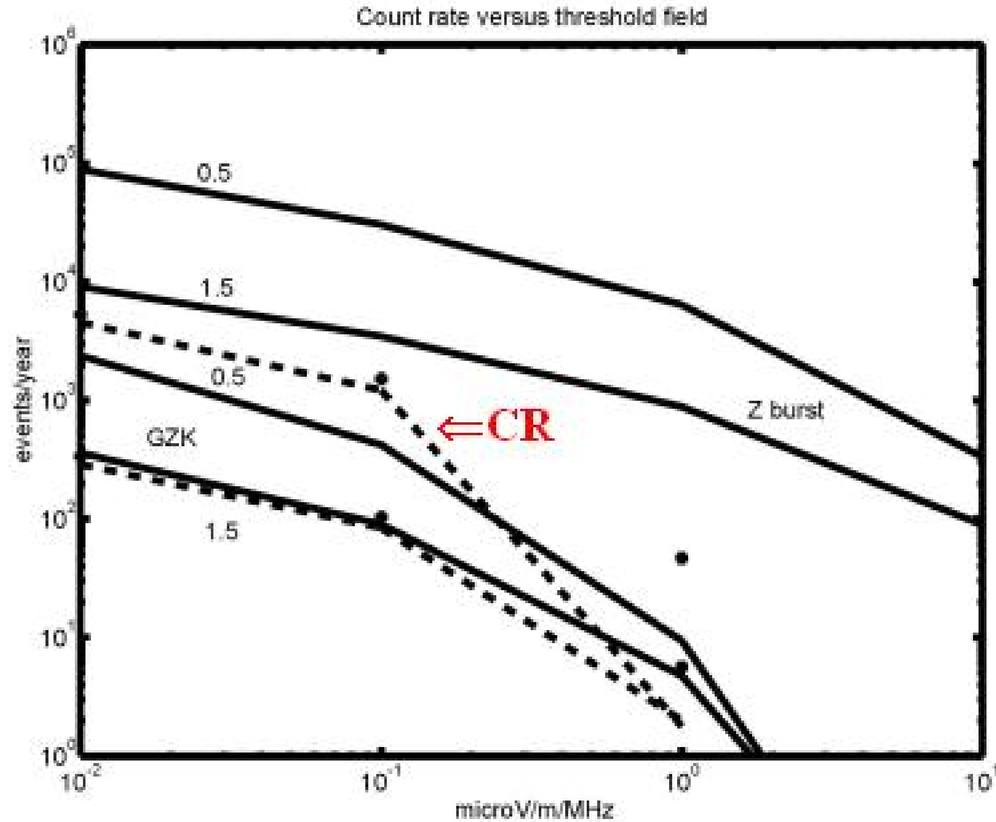


Total aperture for f = 0.5 GHz, E_{th} = 0.01; 0.1; 1 μV/m MHz

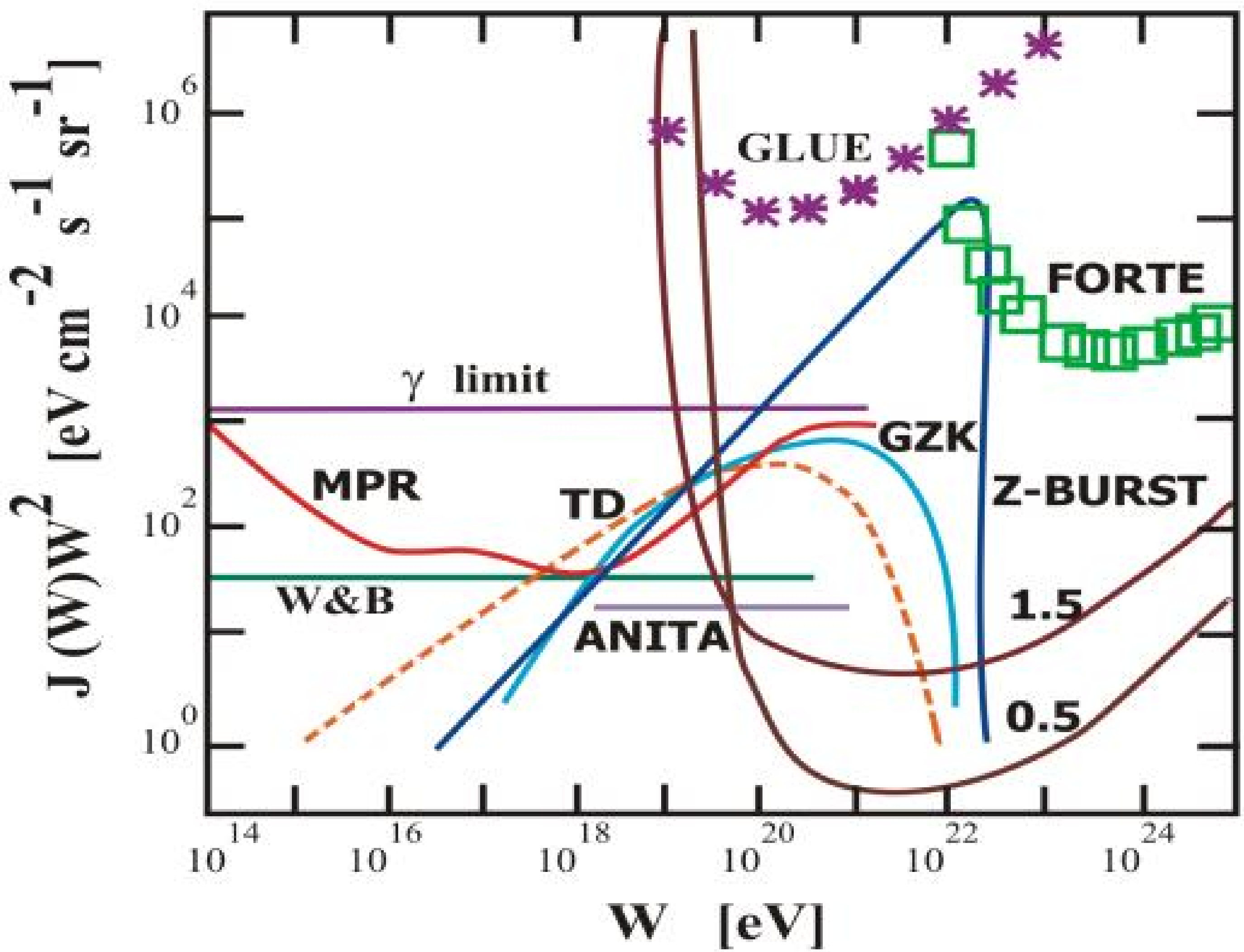


N(events / year, E_{th}) for $W \geq 10^{18}$ eV; (+ no GZK cutoff);

NU: Z-burst and cosmological; f = 0.5 and 1.5 GHz



N(events/year, E_{th}) for $W \geq 10^{20}$ eV



LORD limits on ν flux

1 year

E_{th} =

0.1μV/m MHz;

f = 0.5; 1.5 GHz

Models: TD – topological defects; WB – Waxman, Bahcal;

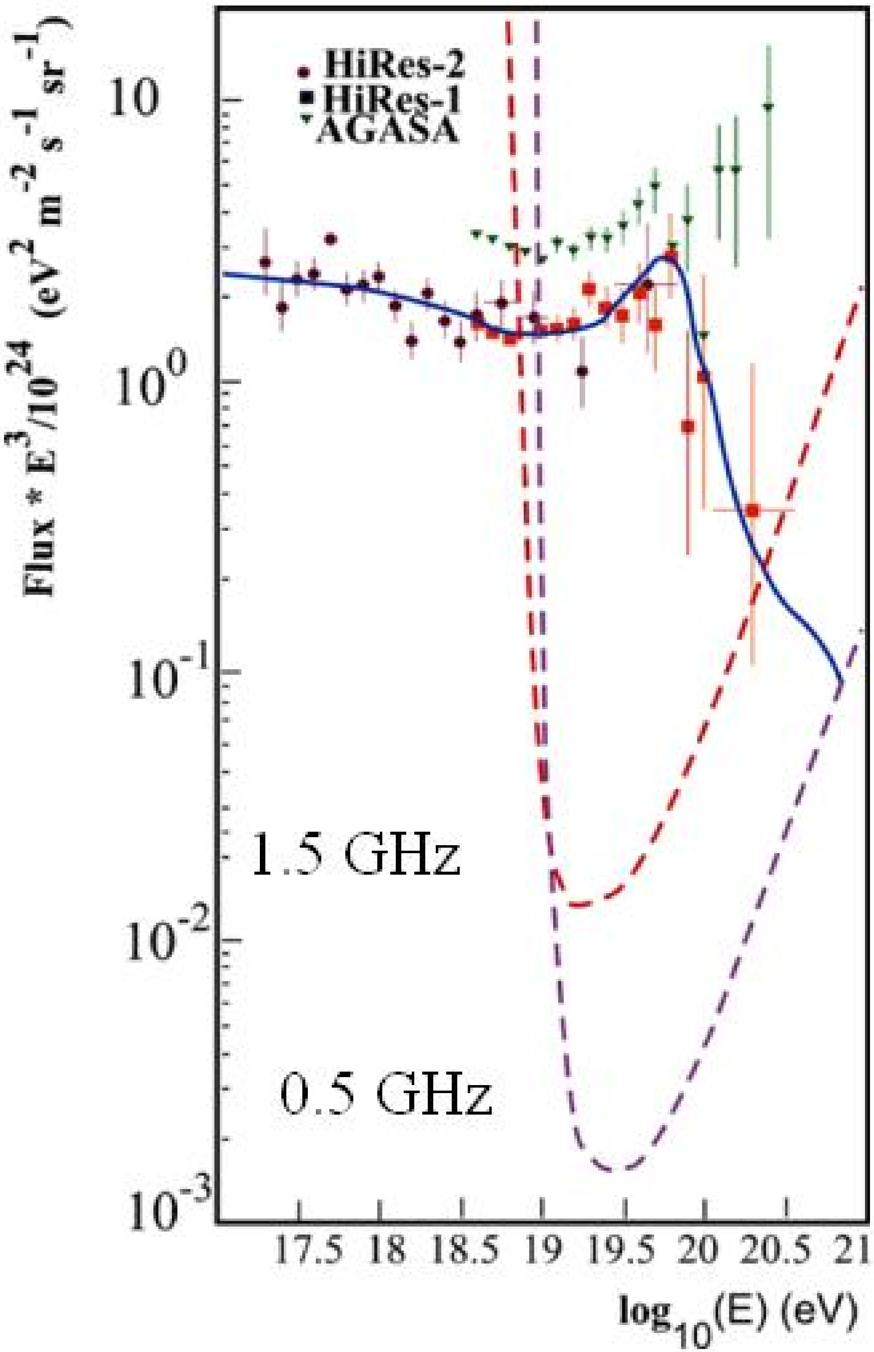
MPR – Mannheim, Proteroe, Rachen

LORD: sensitivity to the CR flux.

f = 0.5; 1.5 GHz

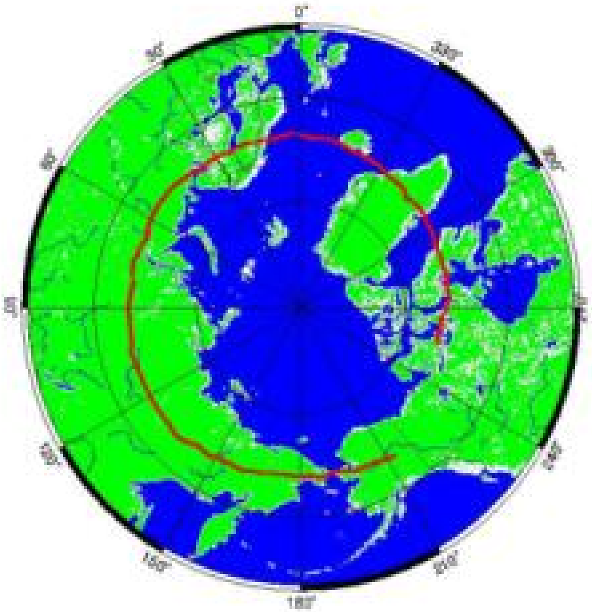
$E_{th} = 0.1\ \mu V/m\ MHz$

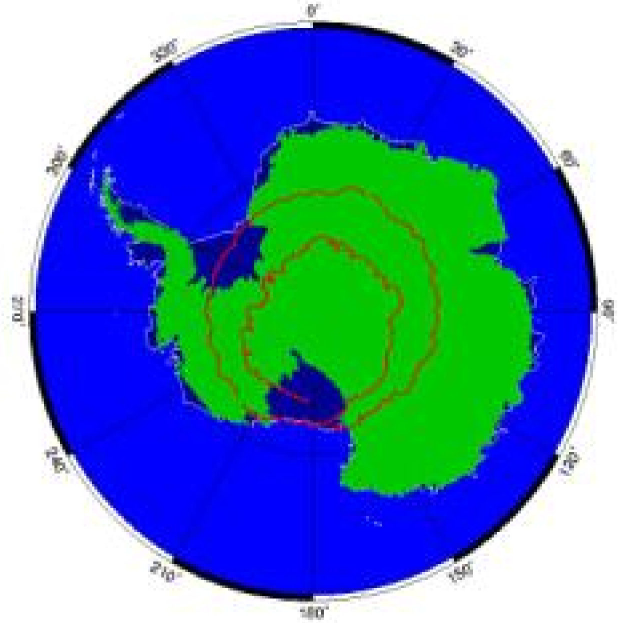
T = 1 year



CREED

(Cosmic Rays of Extreme Energy Detection)





- **The prototype of the lunar (LORD) detector will be tested during high-altitude balloon flight around the North or South Poles**

EXPECTED NUMBER OF EVENTS/CALENDAR YEAR

		CR ($\geq 10^{20}$ eV)	GZK-ν
TRADITIONAL:	AUGER	~ 30	~ 0.5
	EUSO	~ 300	~ 0.1
	OWL	~ 1000	~ 0.2
	ICECUBE	---	~ 1
RADIO:	ANITA	---	~ 20
	SALSA	---	~ 10
	LORD	~ 1000	> 100

V838 Monocerotis Light Echo

CONCLUSION

- We expect that Cherenkov radio method will essentially enhance the capabilities of traditional methods of detection of ultrahigh-energy cosmic rays and neutrinos

- Even the very first measurements (RICE, GLUE, FORTE) allowed constraining some models of the UHEN sources in the previously unexplored energy region.

- It is hoped that further work in the field will provide new important information on the most energetic particles of the Universe

Hubble Heritage

-P. A. Cherenkov gave us a powerful experimental tool, Cherenkov radiation

-In *optical region* it found very wide and efficient applications for CR and particle physics

-Will it be also successful in the *radio-frequency band* for the new frontier studies of the UHE particle physics?

-The answer depends on our ability, skill, and persistence.