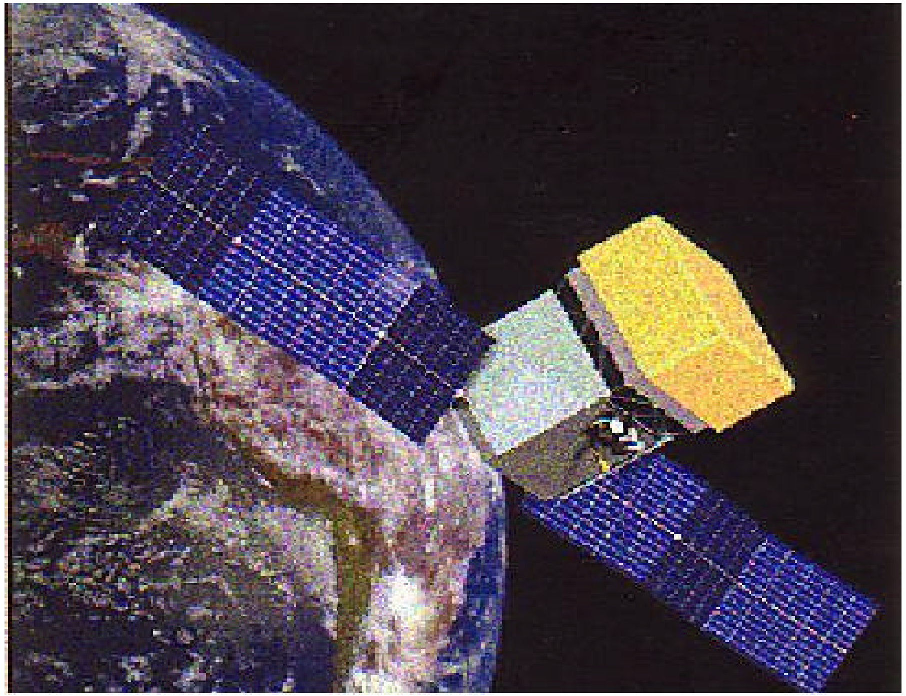
ISAPP 2003

Observations of Cosmic Rays

- Balloon and Satellite Experiments
- Radiodetection
- Neutrino Detection by Telescopes and by Horizontal Air Showers

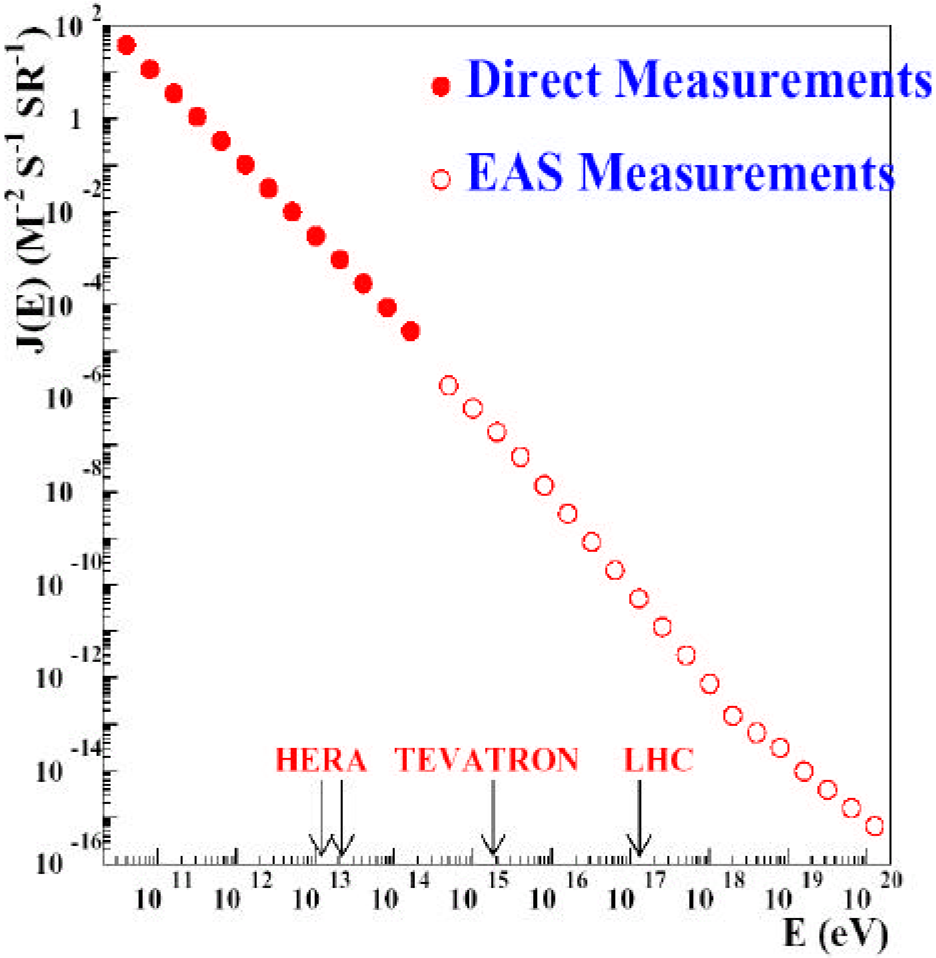
Direct Detection: Balloons and Satellites



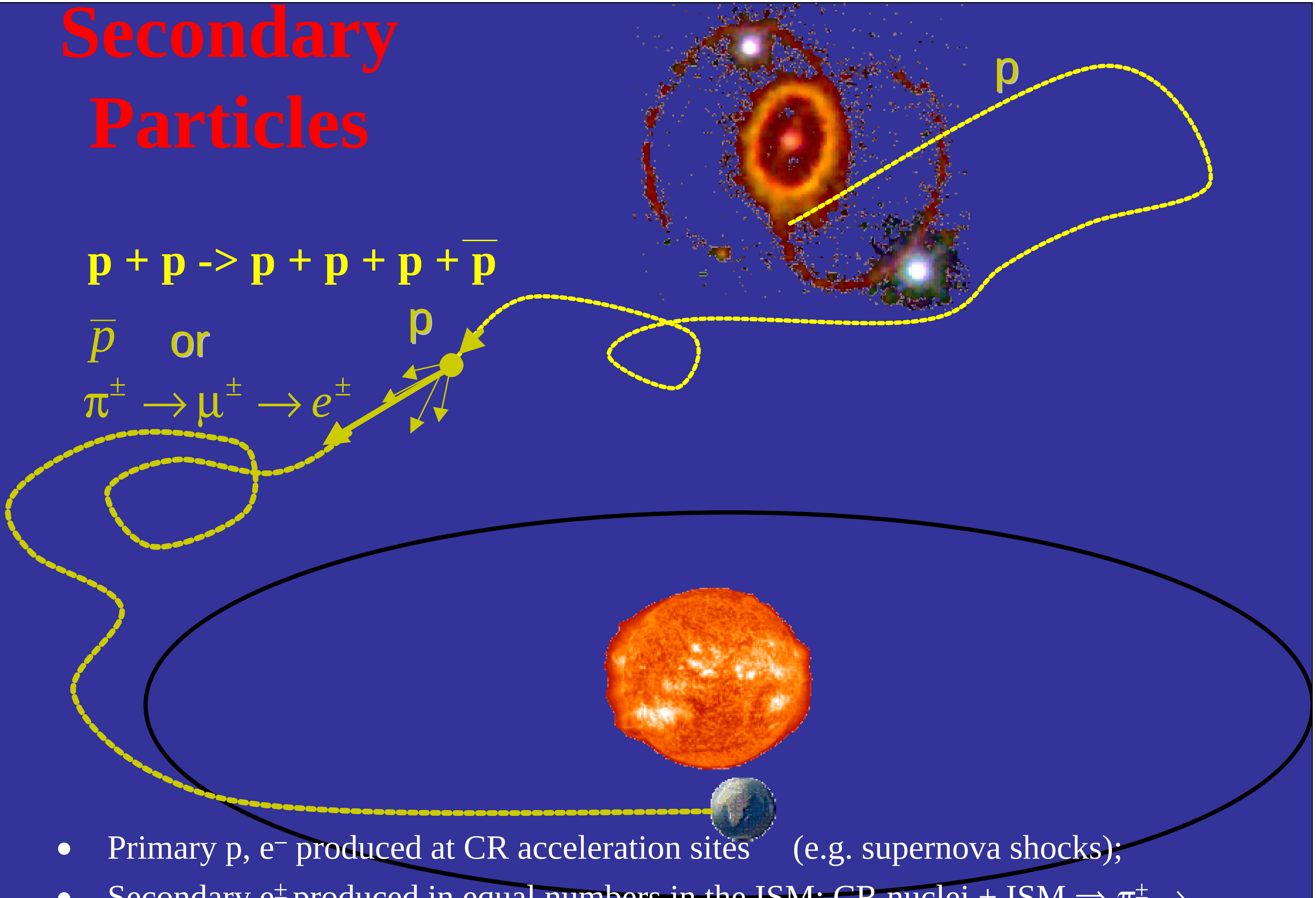
At $<10^{14}$ eV: flux is large enough to allow direct measurements on balloons, satellites, shuttle missions

At $> 10^{17}$ eV: flux $< 10^{-10}$ /m^2 Sr s

A 1m^2, 2π Sr detector sees < 1 event / 50 yrs !



Secondary Particles



$p + p \rightarrow p + p + p + \bar{p}$

$\bar{p}$ or

$\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$

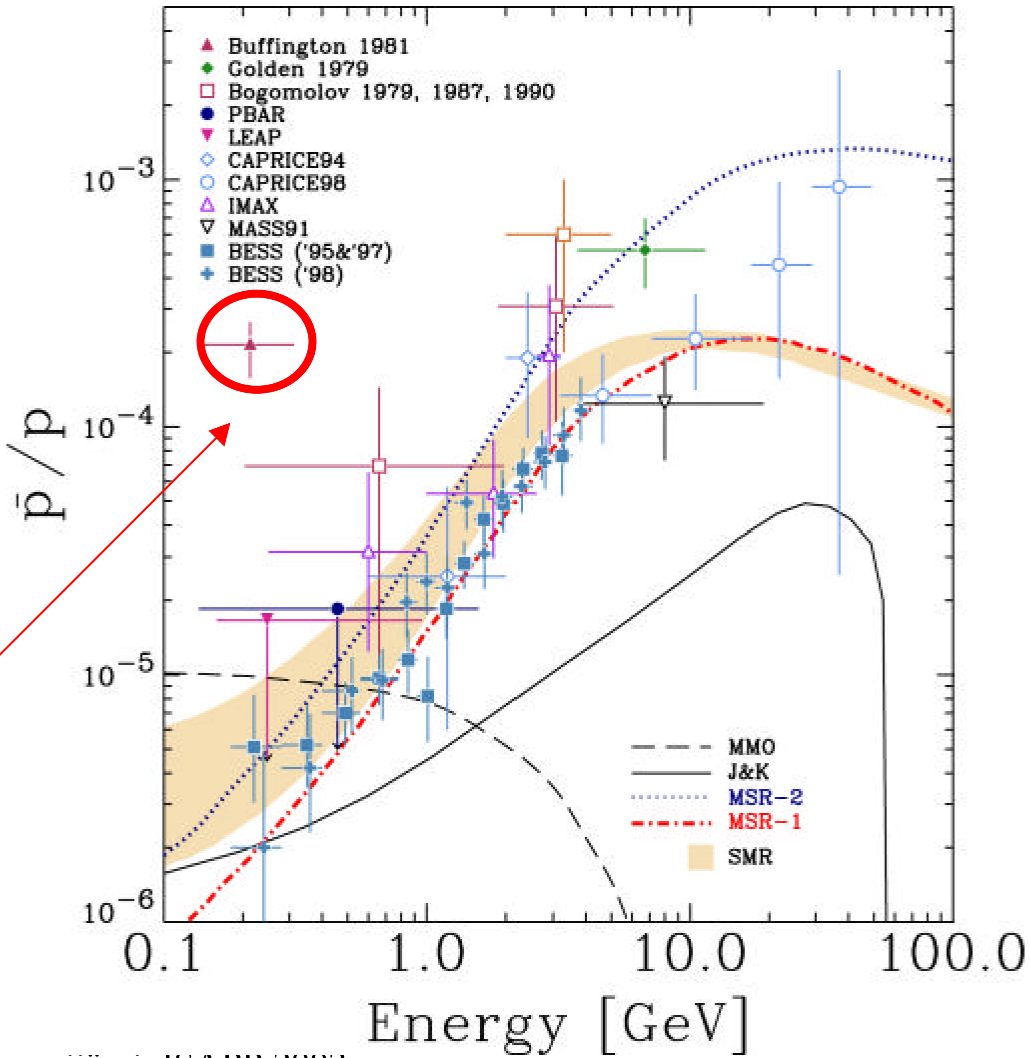
- Primary p, e^{-} produced at CR acceleration sites (e.g. supernova shocks);
- Secondary $e^{\pm}$ produced in equal numbers in the ISM: CR nuclei + ISM $\Rightarrow \pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$;
- Secondary pbars also produced in the ISM;

Experimental Goals

before 2000

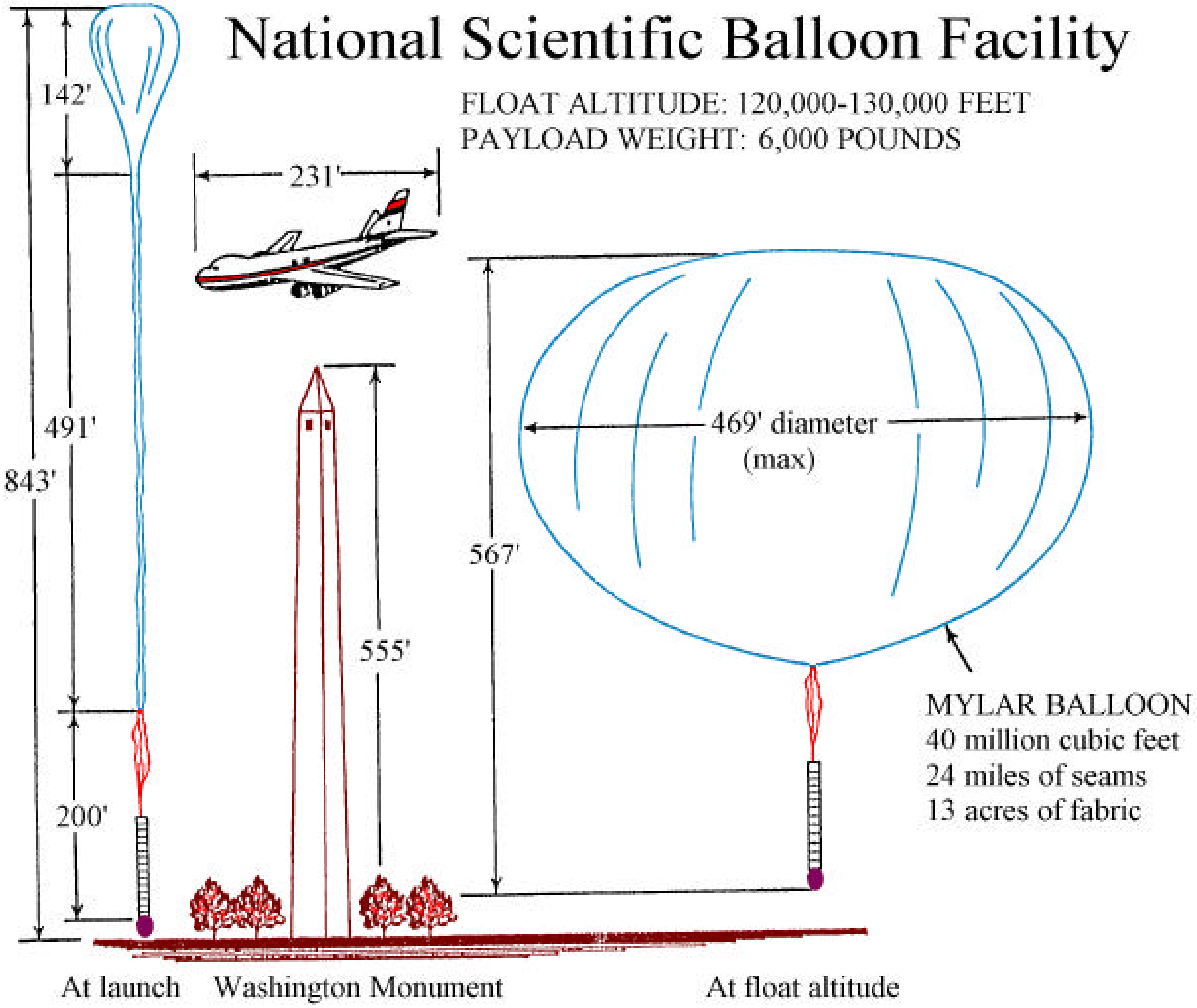
- Antimatter: Positrons, Antiprotons

  Primary or secondary ?
- Searches for heavy antimatter (e.g., Anti-Helium)
- Composition of Cosmic Rays (Z, A)
- Propagation

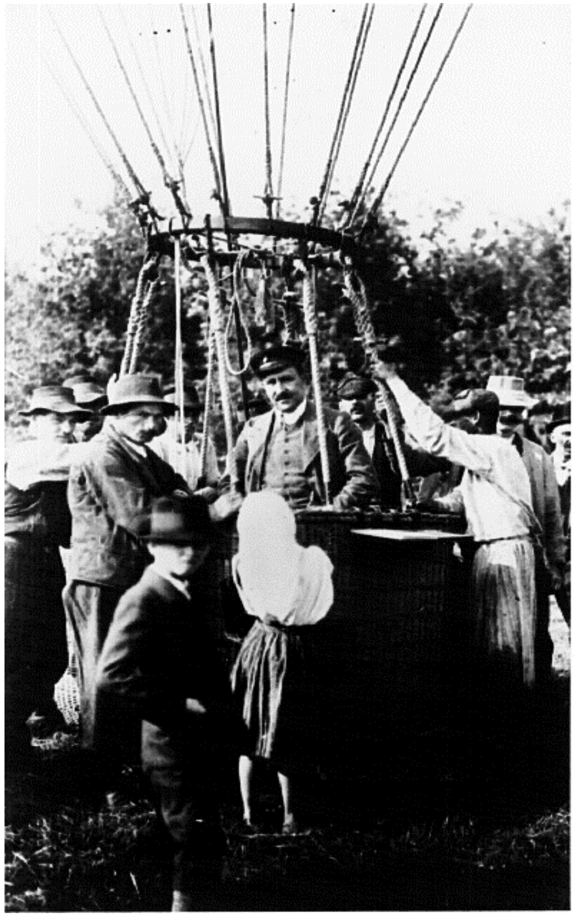


Exotic source ?

Scientific Ballooning



Victor Hess, 1912
17,000 feet



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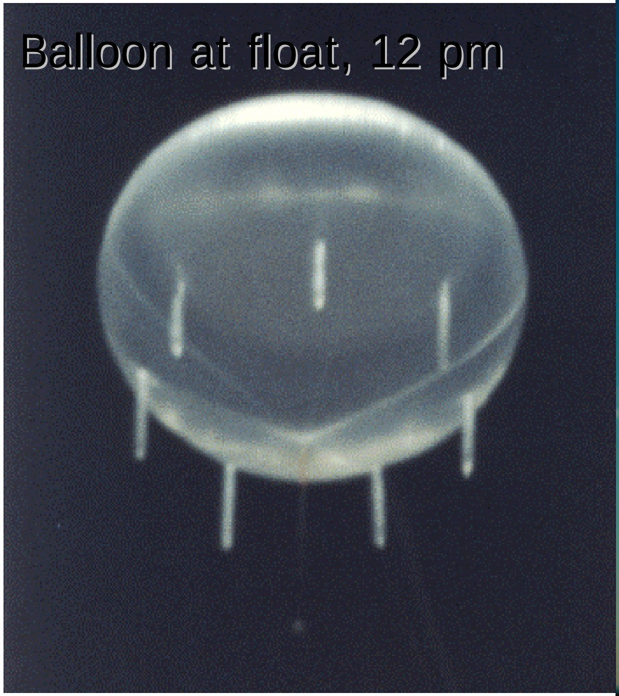
Scientific Ballooning

Crane hook-up
4 am



Balloon at float, 12 pm

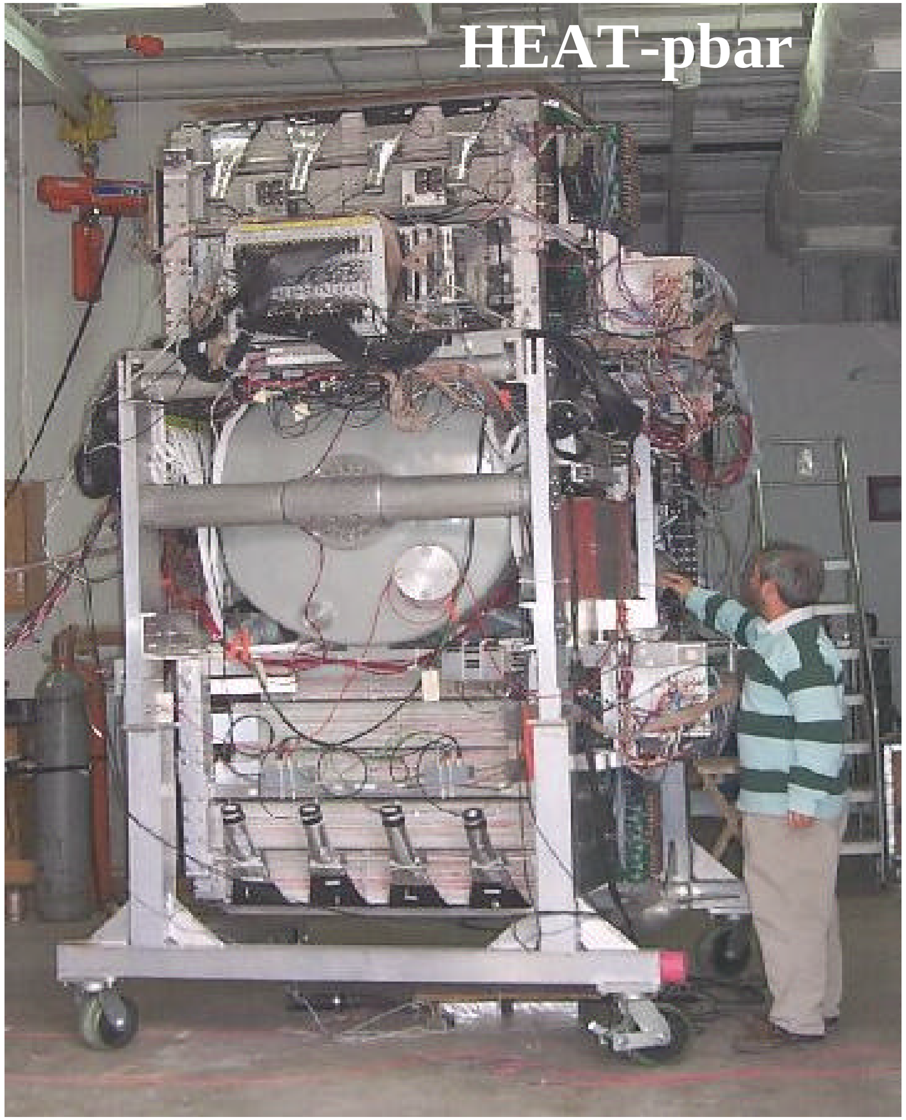
Launch
9 am

Balloon inflation 8 am

HEAT-pbar (High Energy Antimatter Telescope)

- Superconducting Magnet Spectrometer with Drift Tube Hodoscope (DTH), Multiple Ionization (dE/dx) Detector and Time-of-Flight (TOF) system.
- 1) Jun. 2000 flight from Ft. Sumner, NM (22 hour flight)

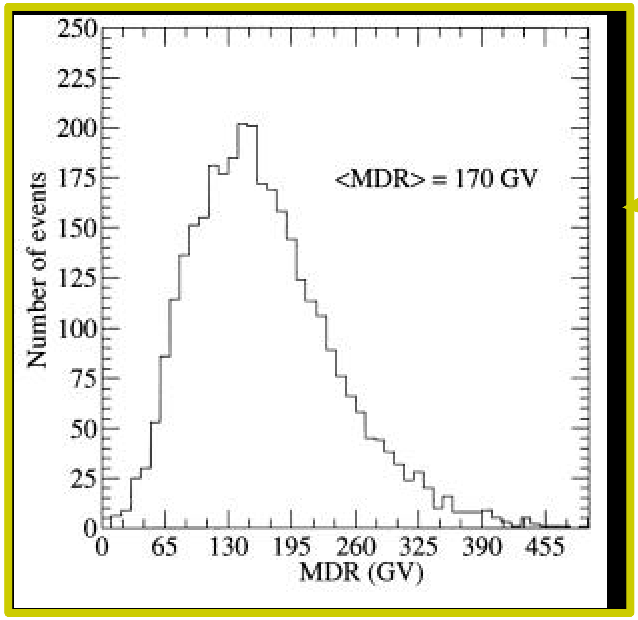
  2) May 2002 flight from Ft. Sumner, NM (6 hour flight; failed balloon)



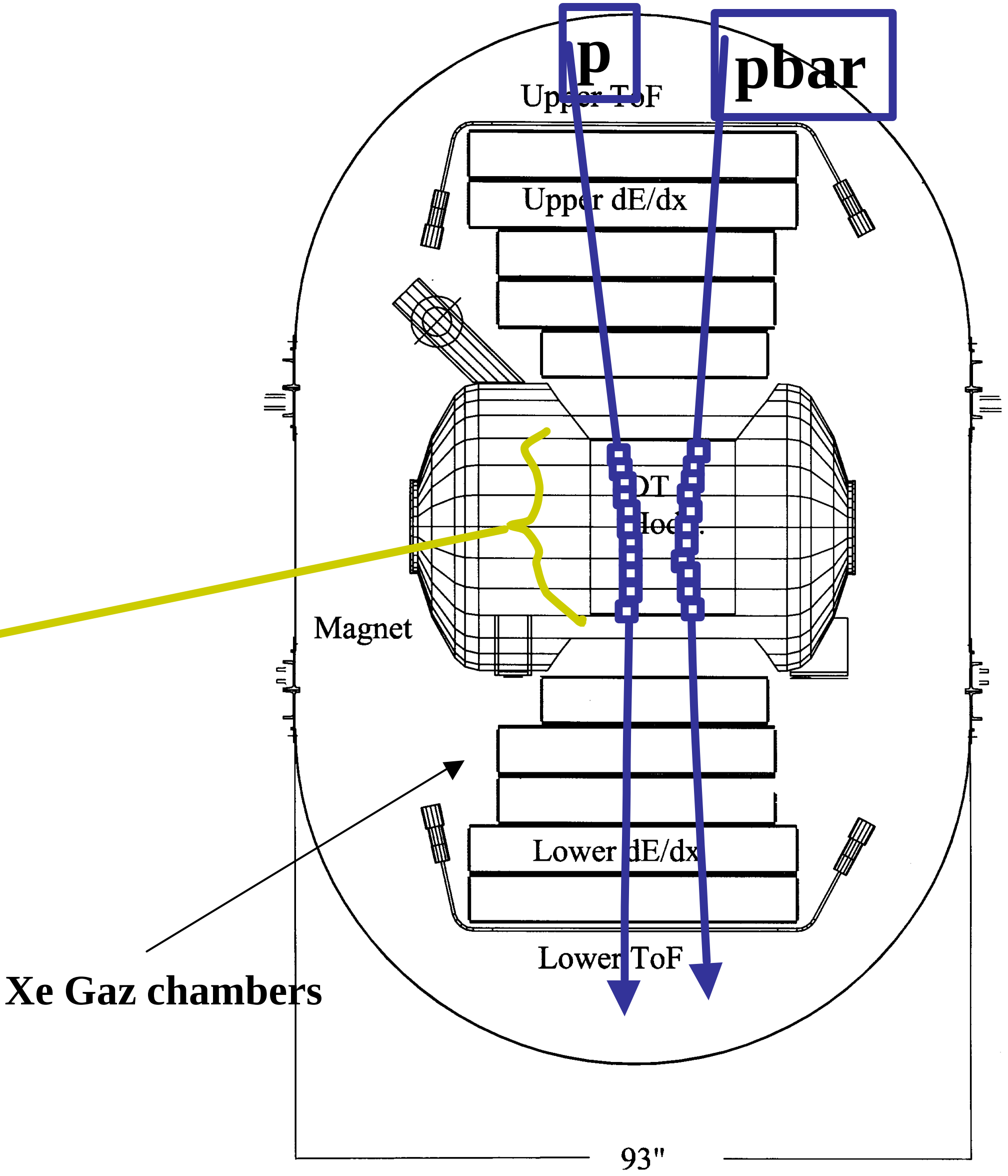
Identifying Antiprotons with HEAT-pbar

- DTH:
  - p from amount of bending in B=1T
  - Sign of Z from direction

$R = pc/Ze$, $p_{max} \sim 54\,GeV/c$

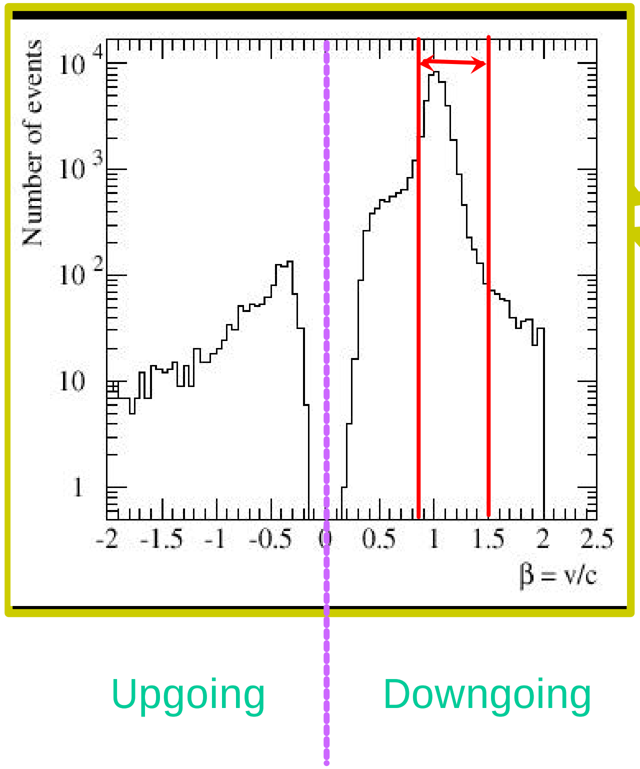


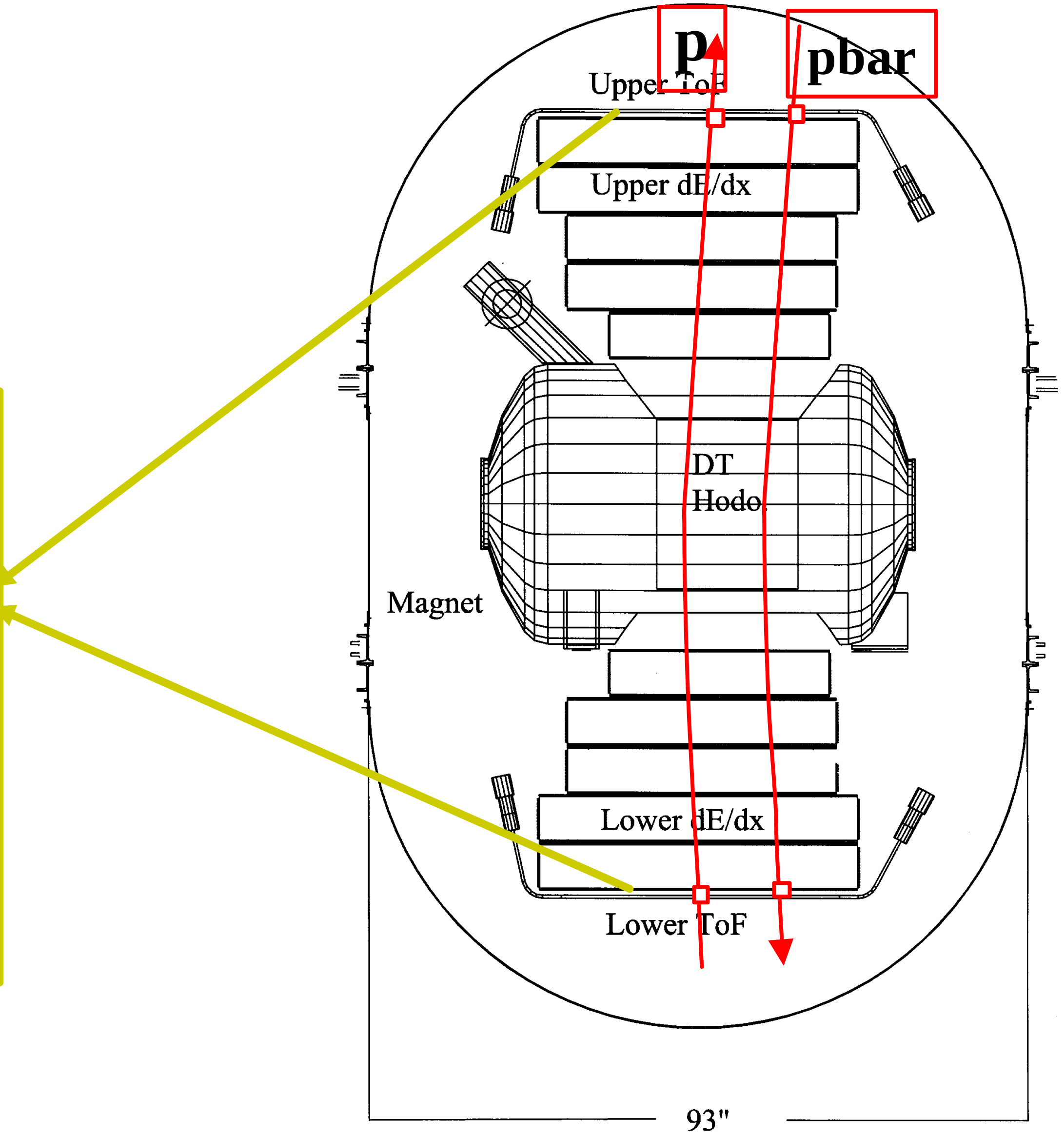
$$\mathrm{MDR} = \frac{3 \cdot d}{\sigma} \sqrt{(N+4)/720} \int \mathbf{B} \bullet \mathbf{dl}$$



Identifying Antiprotons with HEAT-pbar

Up going proton (albedo particles) looks like down going antiproton -> Need to know start and stop in the time-of-flight



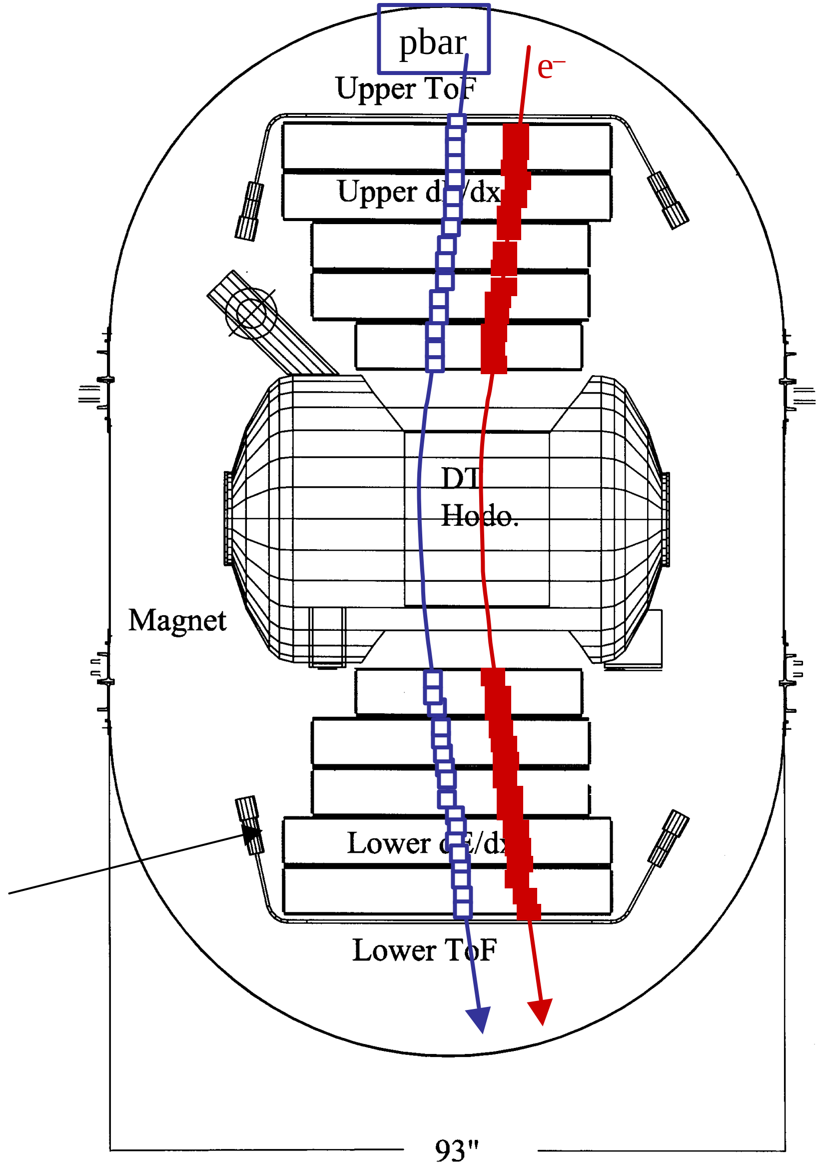


Identifying Antiprotons with HEAT-pbar

- Multiple dE/dx: p / π-μ / e separation

Technique exploits the logarithmic rise in the mean rate of energy loss (Bethe-Bloch):

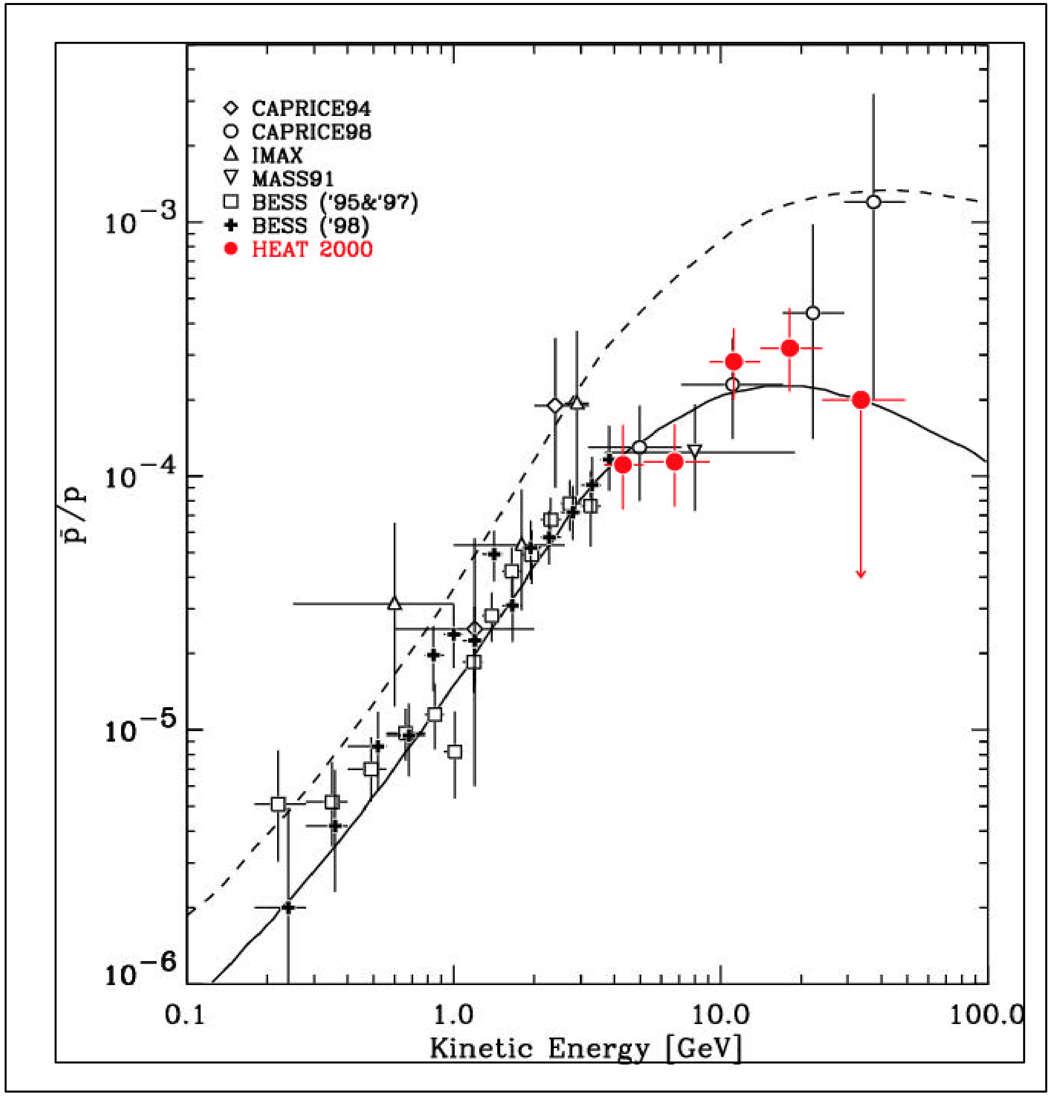
$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$



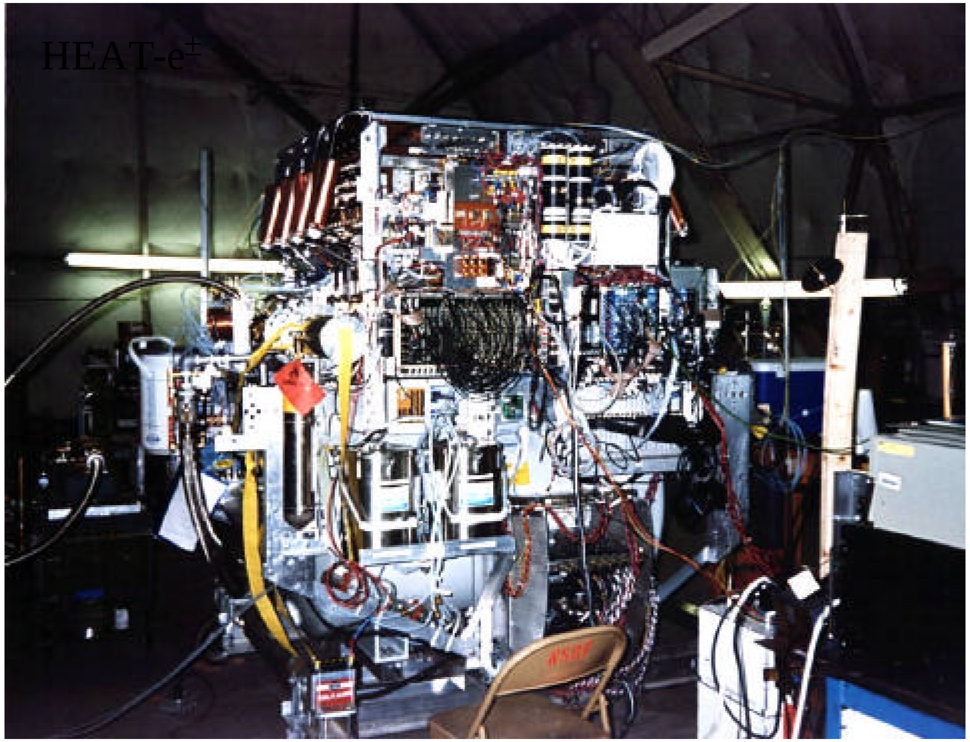
Xe Gaz chambers

Experimental Results

- BESS, IMAX, MASS, CAPRICE and HEAT data in agreement with secondary production expectations;



HEAT-e± (High Energy Antimatter Telescope)

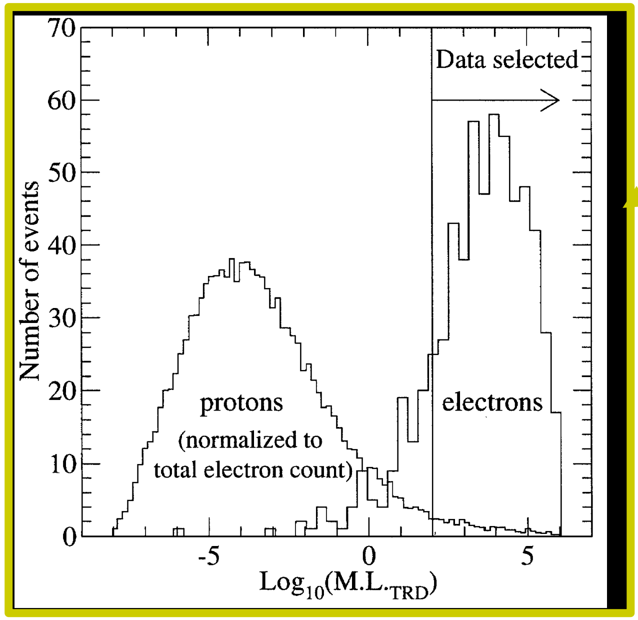


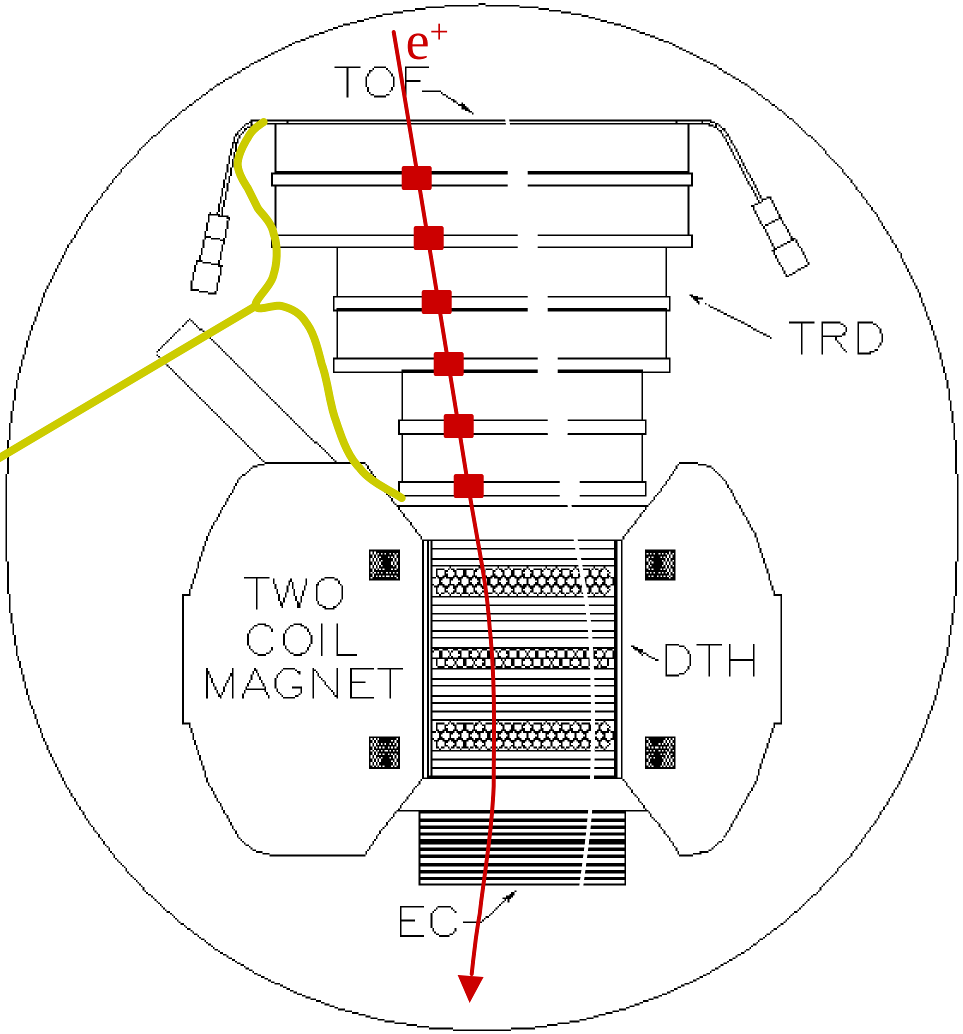
- Superconducting Magnet Spectrometer with Drift Tube Hodoscope (DTH), Electromagnetic Calorimeter (EC), Transition Radiation Detector (TRD) and Time-of-Flight (TOF) system.
- 1) May 1994 flight from Ft. Sumner, NM (29.5 hour flight)

  2) Aug. 1995 flight from Lynn Lake, Manitoba (26 hour flight)

Identifying Positrons with HEAT-$e^{\pm}$

- TOF, DTH: same as HEAT-pbar
- TRD:
  - dE/dx losses in MWPC
  - TR for $e^{\pm}$ ($\gamma = E/mc^2 > 4\times10^3$)

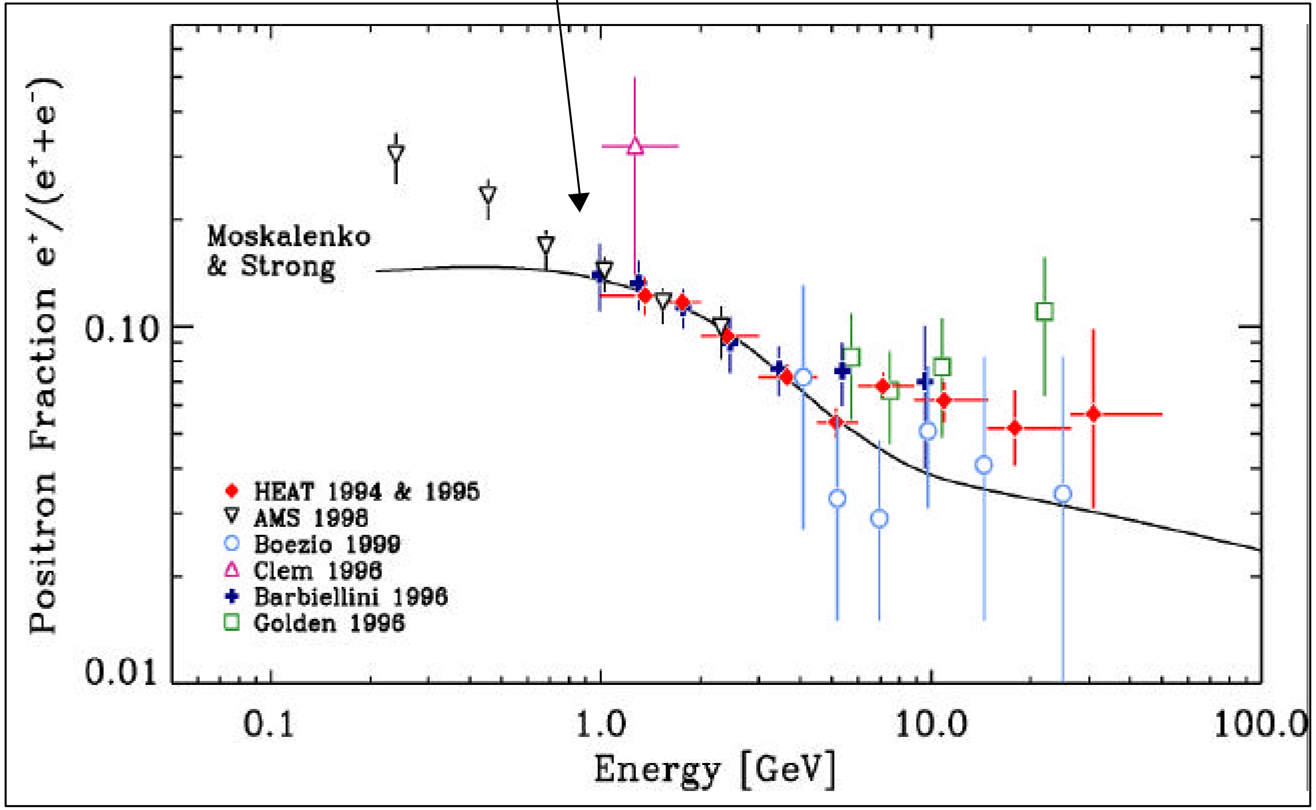




Positron Fraction since 1995

- New detailed model predictions of e$^+$, pbar, γ production and propagation;
- Results much closer to secondary production expectations.

Effects of Solar modulation below GeV

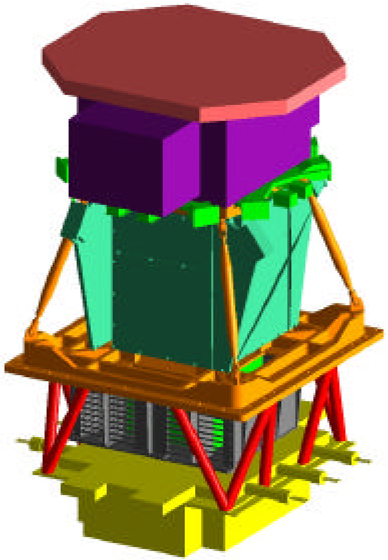


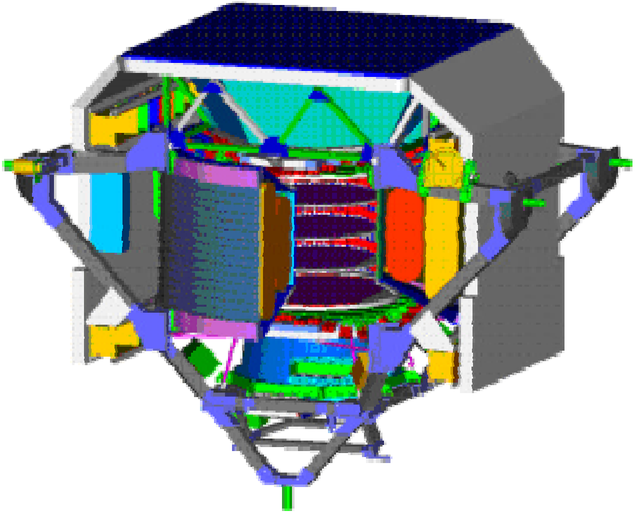
Outlook

- Continuing balloon spectrometer measurements: BESS, HEAT.
- New space experiments:
  - PAMELA (Satellite, 2004 launch from Baikonur, 3 year mission, 0.4 – 200 GeV?);
  - AMS (ISS, 2005 launch ? on STS, 3 year mission, 0.1 – 200 GeV?).

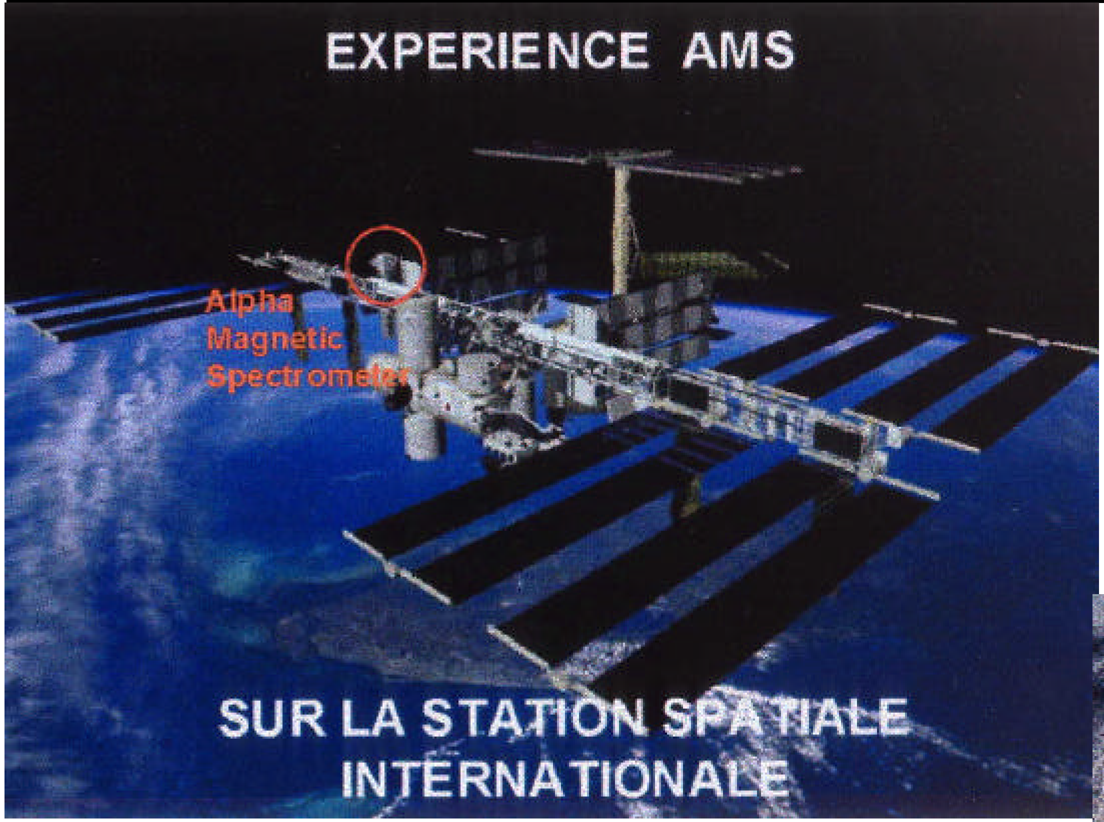
PAMELA Russian-Italian Mission
2004 Baikonur launch
3 yrs: ~ 30 × balloon exposure

AMS
2005 STS launch ?
3 yrs: ~ 900 × balloon exposure



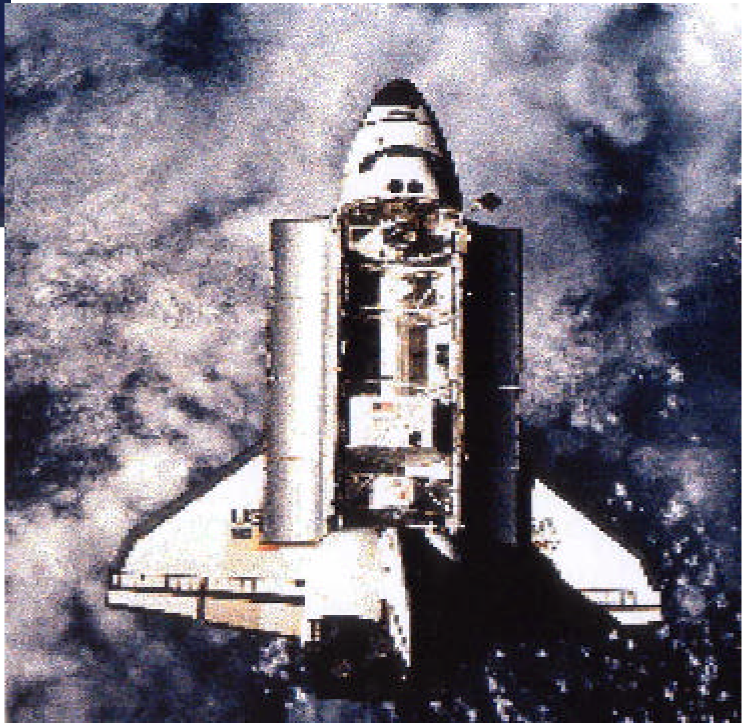


Alpha Magnetic Spectrometer AMS 02



Cosmic rays with energies GeV - TeV
Search for antimatter
Indirect search for dark matter

Particle identification including charge sign reconstruction



Alpha Magnetic Spectrometer

AMS 02

(Exploded View)

Transition Radiation Detector : **separate e/p up**

Foam + Straw Drift Tubes (Xe/CO_2) **to 300 GeV**

Time of Flight Upper : **trigger, β**

scintillators, Δt =~120ps **up/down**

Superconducting Magnet :

$BL^2 = 0.85\ Tm^2$

Rigidity up to 1 TeV

charge separation, β

Tracker (8 layers) :

double sided silicon strips, total of $6m^2$

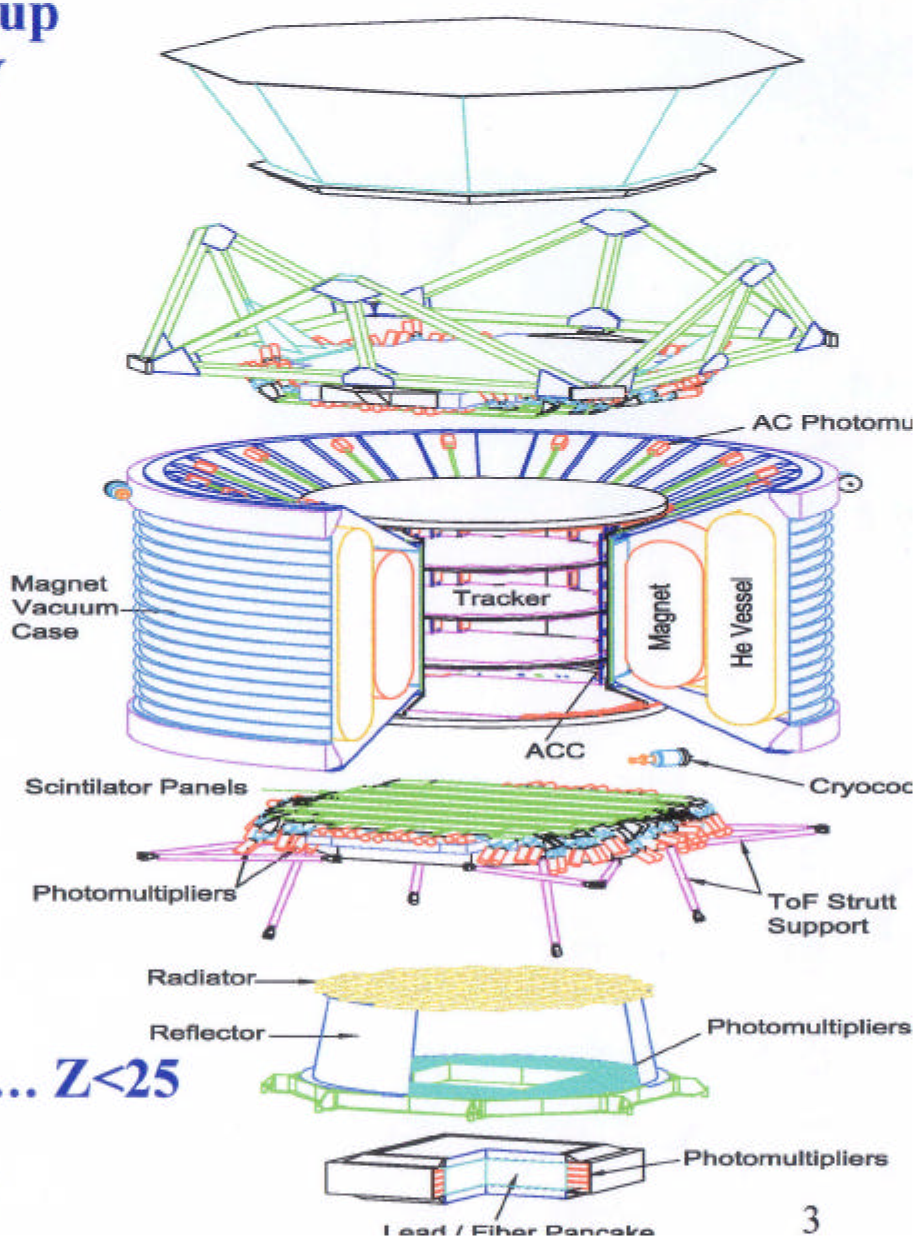
Time of Flight Lower (+ trigger) :

scintillators, Δt =~120ps

RICH :

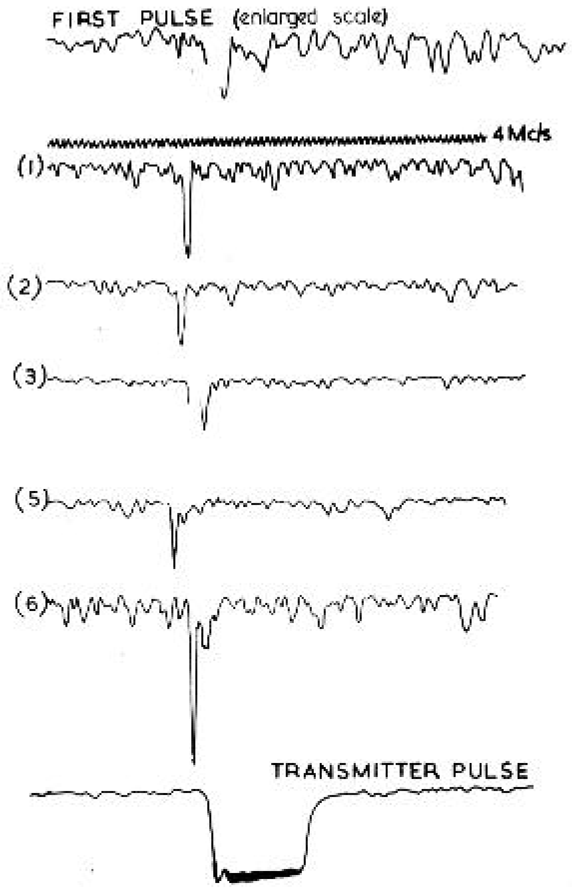
Radiator (Aerogel,NAF) **β, Z^2** **He^3,He^4,B,C ... Z<25**

Electromagnetic Calorimeter : **$e^\pm,\gamma$ to 1 TeV**



Radio Emission from Cosmic Ray Showers

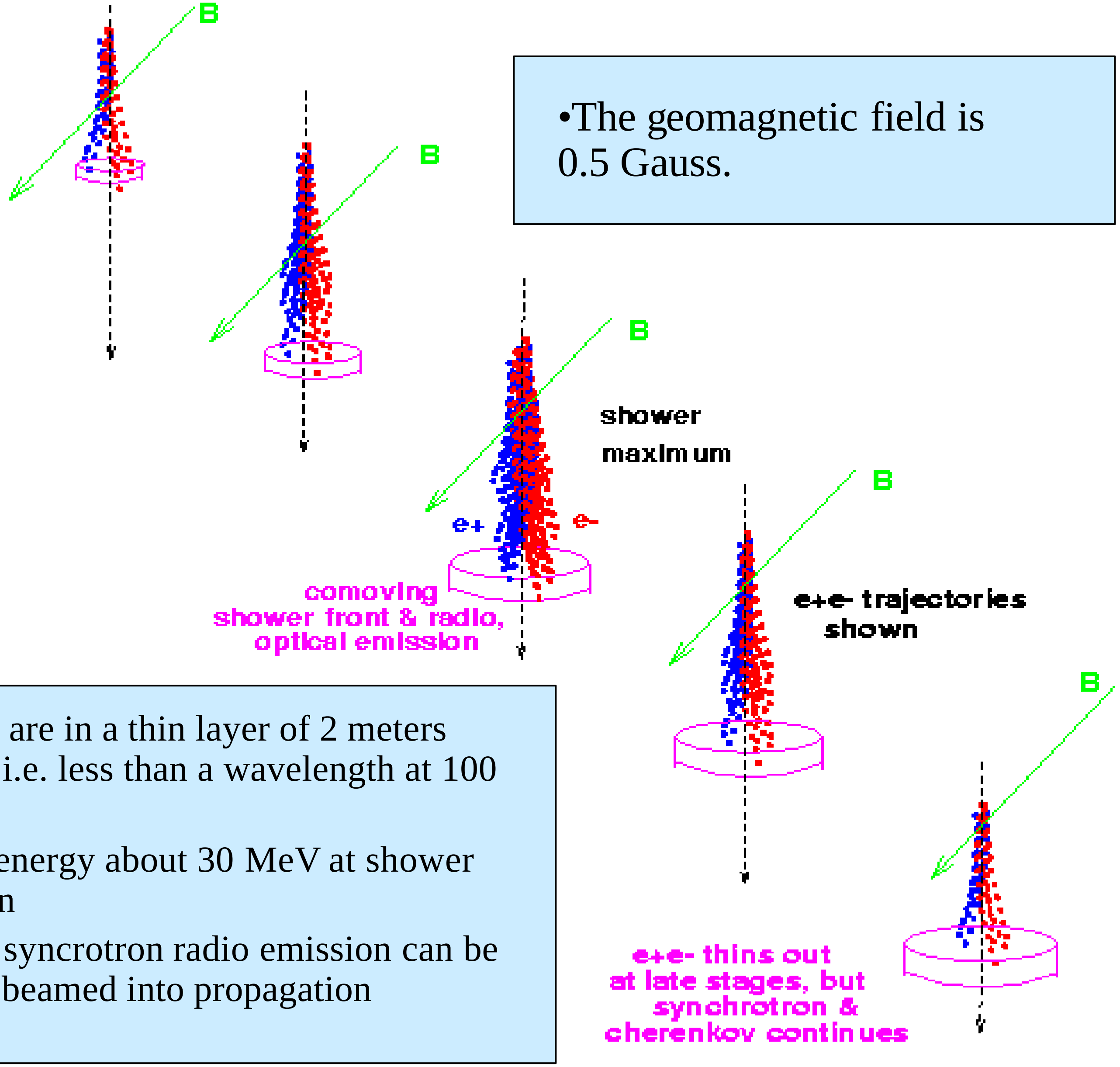
- First discovery: Jelley et al. (1965), Jodrell Bank at 44 MHz.
- Firework of activities around the world in the late 60ies & early 70ies.
- In the late 70ies radio astronomy moved to higher frequencies and also CR work ceased.



Jelley et al. (1965)

Radiation Mechanism: Coherent Geo-Synchrotron

- The geomagnetic field is 0.5 Gauss.

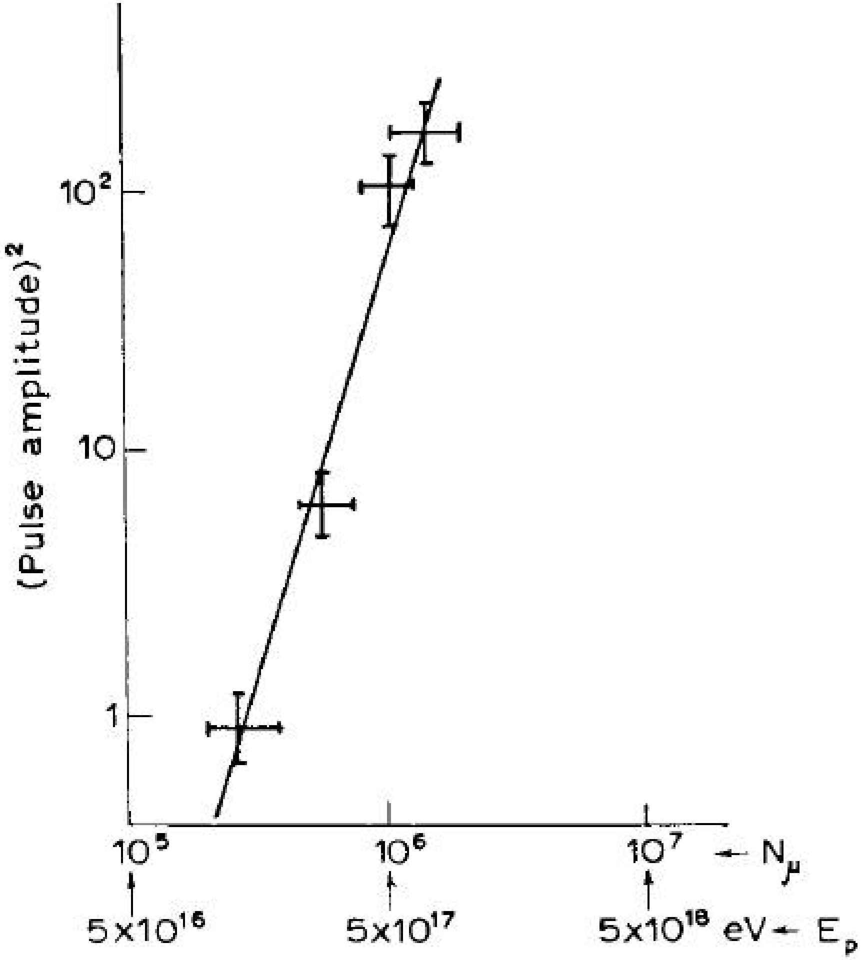


- Electrons are in a thin layer of 2 meters thickness, i.e. less than a wavelength at 100 MHz
- Electron energy about 30 MeV at shower max region
- Coherent syncrotron radio emission can be produced, beamed into propagation direction.

Radio Properties of Air Showers: Energy Dependence of Amplitude

- Experimental results suggest a quadratic dependence of radio flux on particle energy.
- Particle number: $N_e \sim E_\mathrm{p}/\mathrm{GeV}$
- Coherent radiation:

$$e \propto N_e \propto E_\mathrm{p} \;\&\; S_n \propto e^2 \Rightarrow S_\nu \propto E_\mathrm{p}^2$$



Vernov et al. (1968)

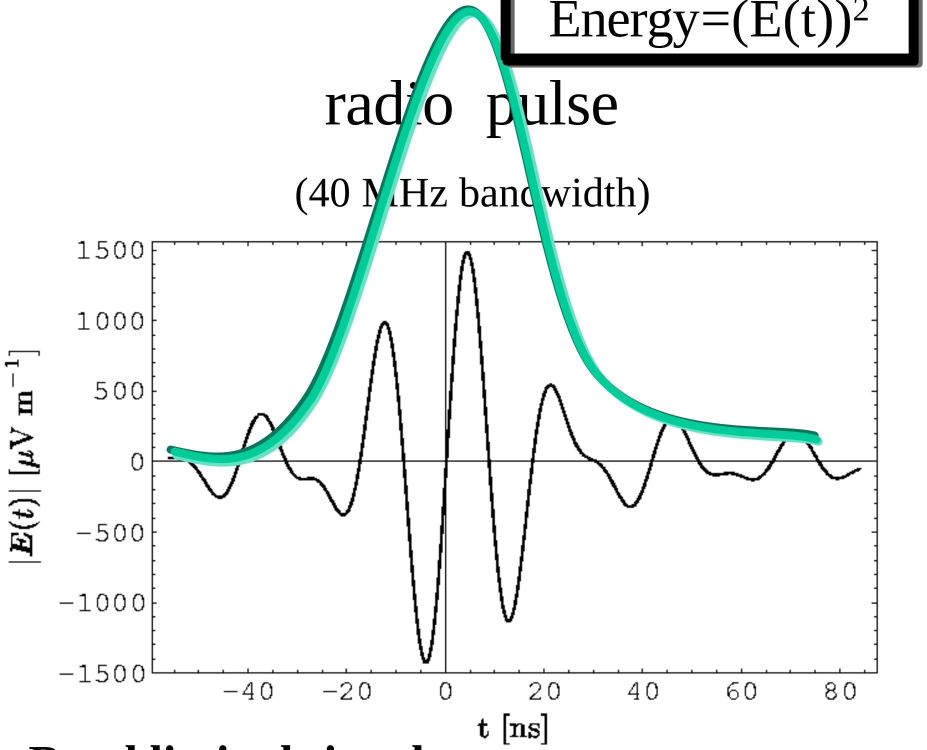
Radio Pulse Spectrum

- Measurements at four frequencies between 44 and 408 MHz (Spencer 1969)
- Noise level favors observations at 40-50 MHz.

Energy=$(E(t))^2$

radio pulse

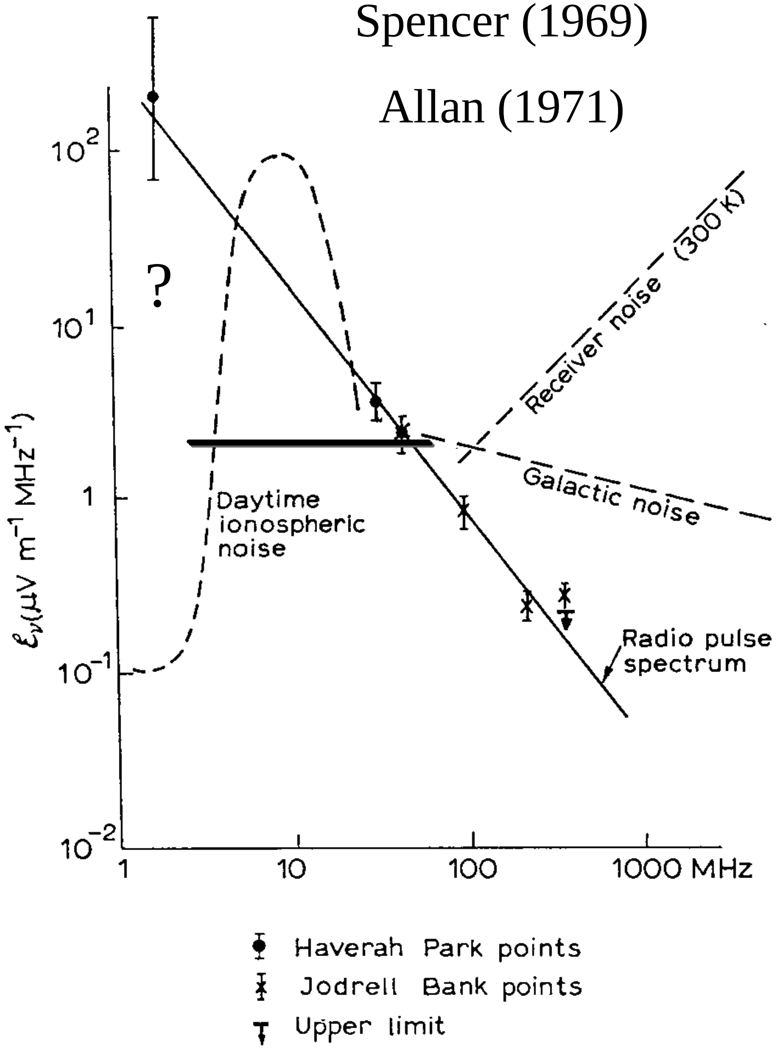
(40 MHz bandwidth)



Band limited signal

Spencer (1969)

Allan (1971)



Radio Emission from Showers in Dense Media: Radio Cherenkov

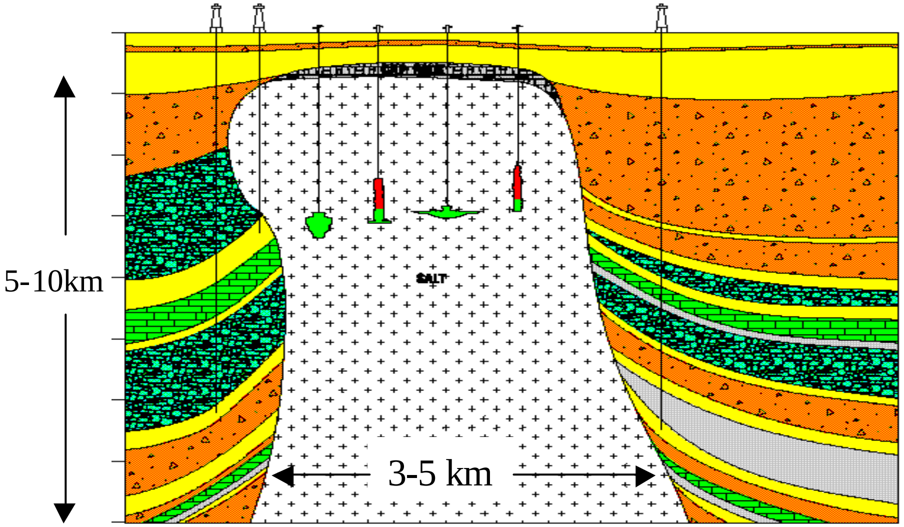
Askaryan process: coherent radio Cherenkov emission

Has been measured with the beam at SLAC !

- EM cascades produce a charge asymmetry, more electrons than positrons, thus a radio pulse
- Process is coherent ➔ Quadratic rise of power with cascade energy
- Radio emission in the range of 100 MHz to few GHz.

Detector Media for Radio Cherenkov Detection

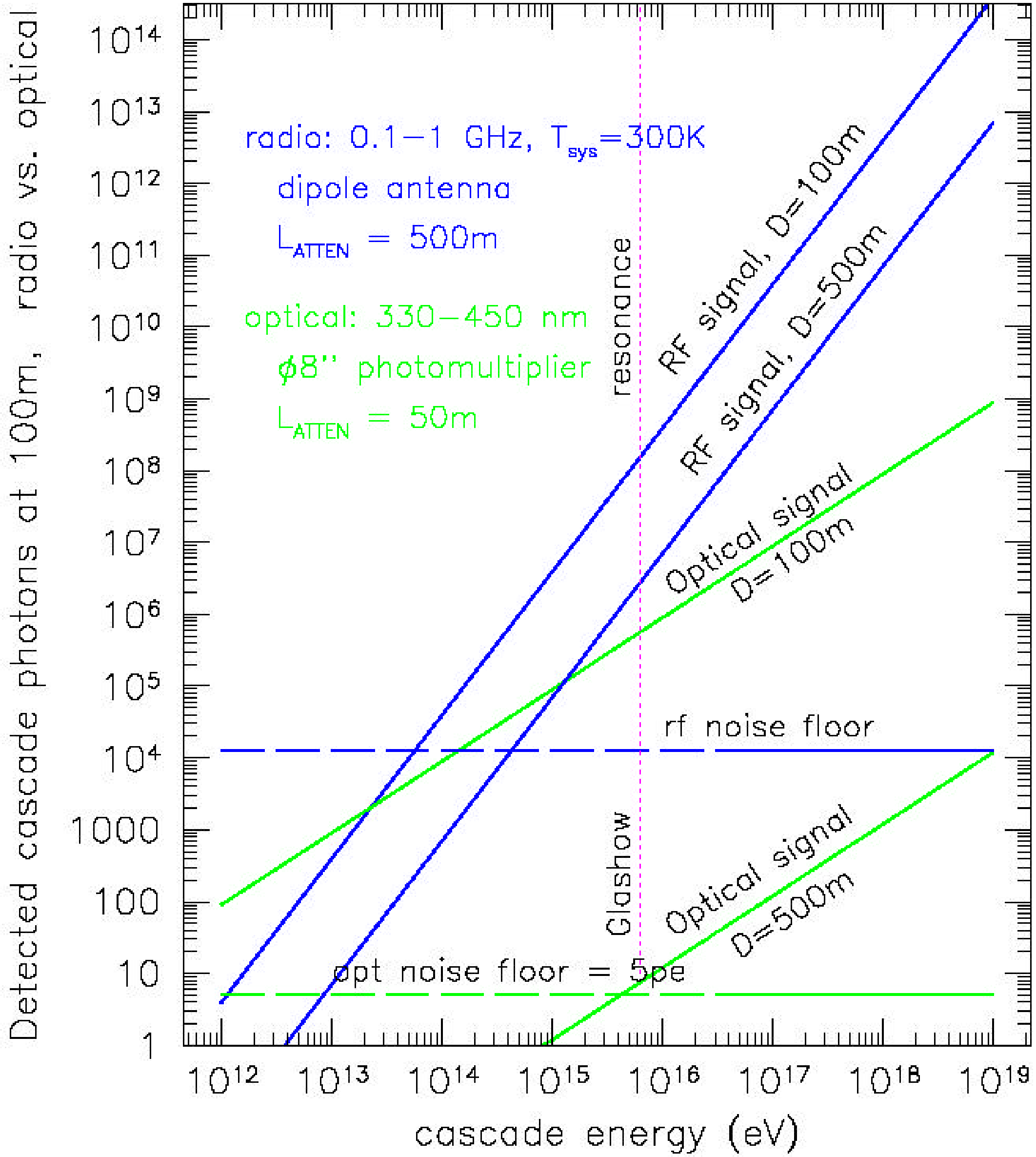
Low RF losses, high density:
Ice, Natural salt, Lunar regolith surface (higher losses but huge radiator)



- Natural salt can be extremely low RF loss:
~ as clear as very cold ice, 2.4 times as dense

- Typical salt dome halite is comparable to
ice at -40C for RF clarity

Radio Emission / Optical Signals



- Compare case of optical & radio detectors in Antarctic ice:
  - optical: 8” photomultipliers typical, good match for blue Cherenkov light
  - attenuation / scattering in ice limits detection at large D
  - Radio: dipole antenna assumed, ice nearly lossless below 1 GHz

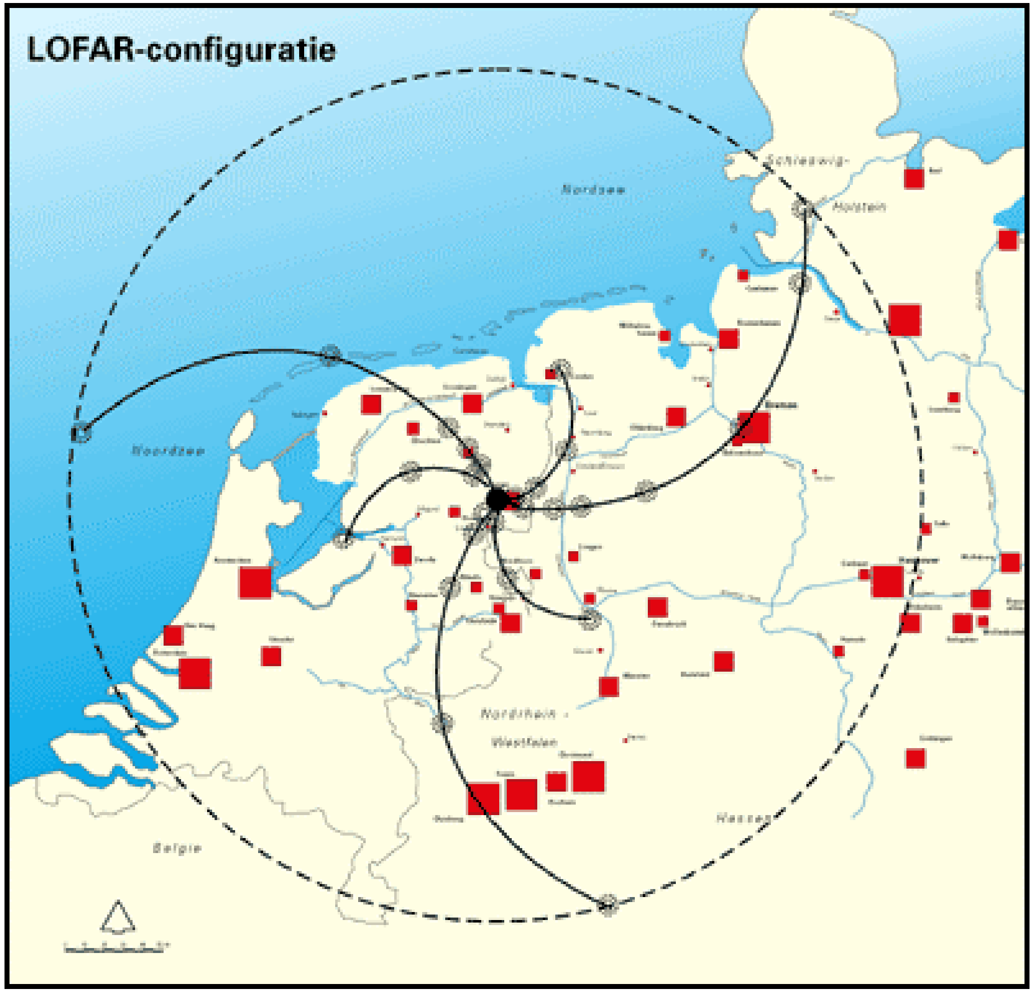
For >>PeV cascade detection:

- optical techniques proven, but radio will dominate over optical for coarse detector spacing (& therefore cost effectiveness)

Examples of Experiments with Radiodetection

LOFAR – a New Digital Radio Telescope

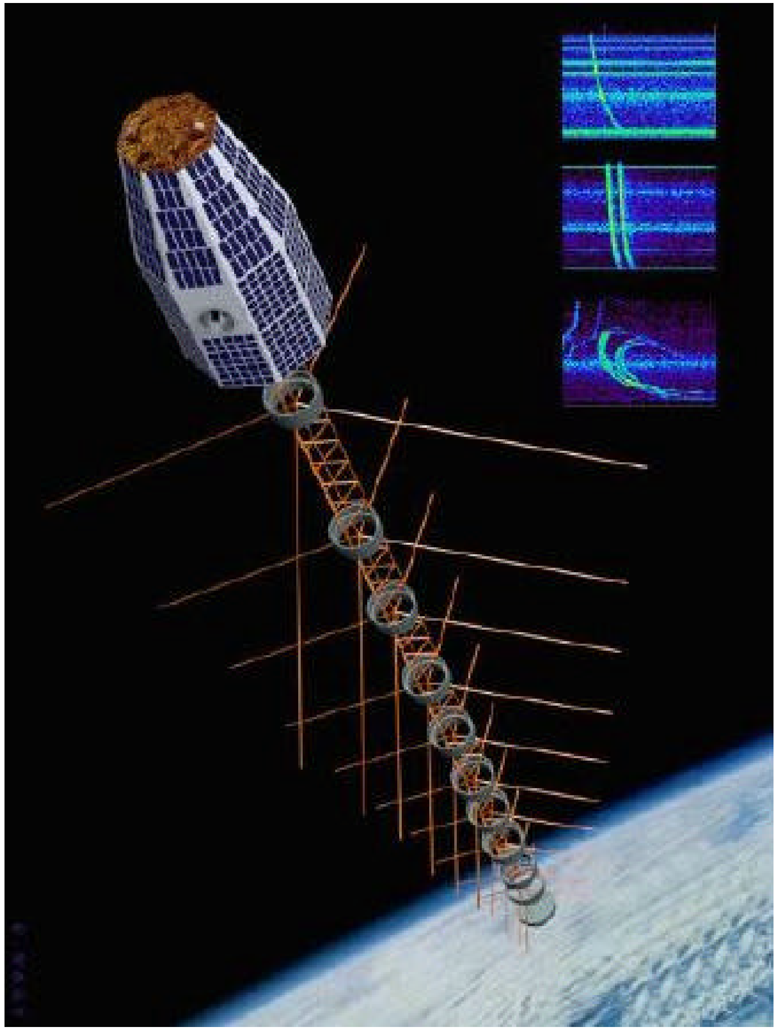
- Low-Frequency Radio Array connected by high-speed internet (25 Tb/sec!)
- Monitors almost entire sky
- Astrophysics
- Will certainly see meteorites and air showers!
- Construction 2004-2006.



LOFAR

- 10^2 stations with 10^2 dipoles/antennas each, connected to a central computer supercluster
- Low-Tech „Hardware“
- “Next Generation” computing and internet (Lucent, KPN)
- No mechanical steering – beam is digitally synthesized
- Radically new telescope concept which is ideally suited for astroparticle-physics (radio air showers).

FORTE: A space-based EHE neutrino & cosmic ray detector?



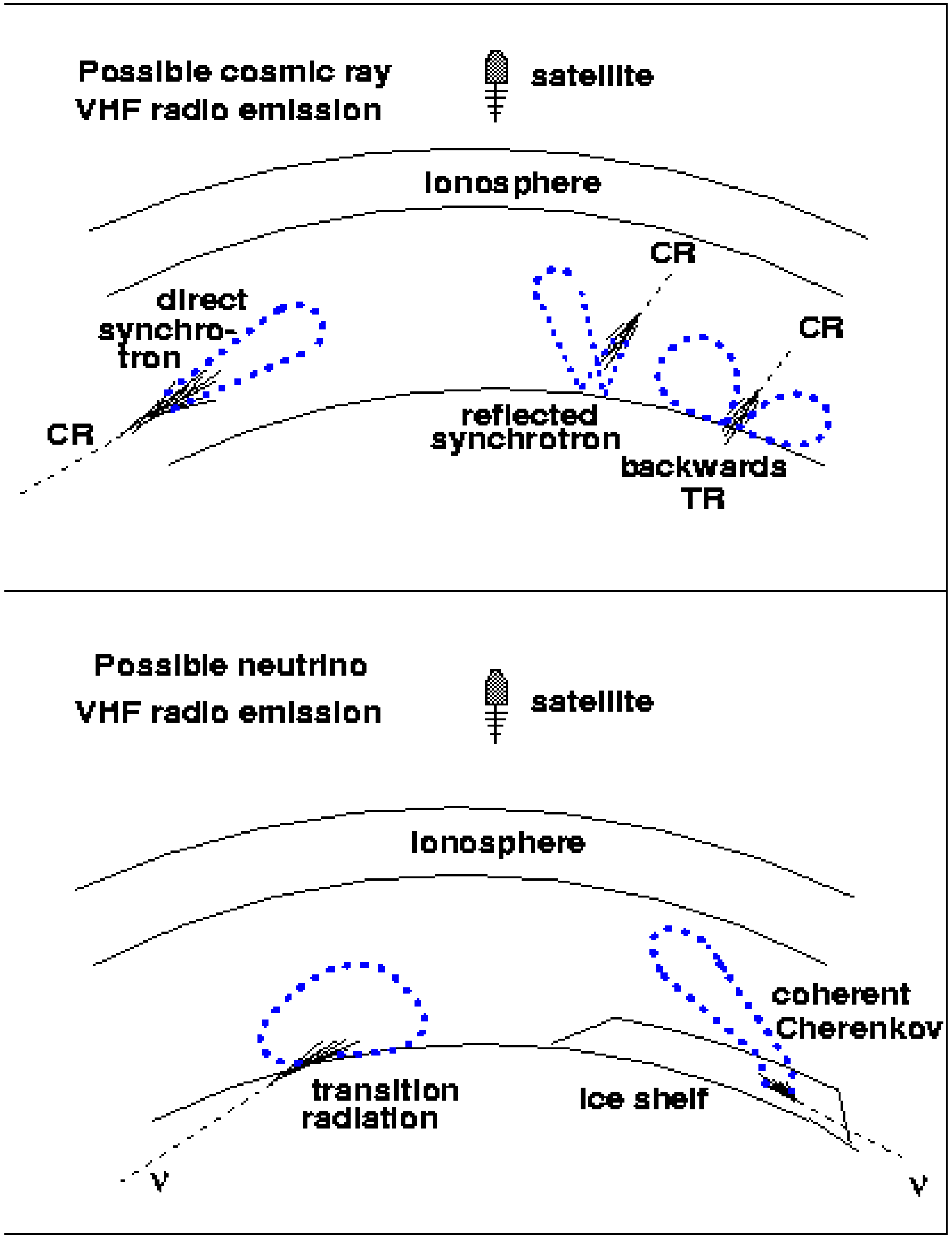
Fast On-orbit Recording of Transient Events

- Pegasus launch in mid-1997, 800km orbit
  - Testbed for nuclear verification sensing
  - US DOE funded, LANL/Sandia ops
  - Scientific program in lightning & related atmospheric discharges

- 30-300 MHz (VHF) frequency range
  - ~3M impulsive triggers recorded to date

- FORTE can trigger on radio emission from giant air showers at E~100 EeV
  - Preliminary estimates: could be ~50 10^{20} eV cosmic ray events in sample
  - Distinct from lightning, could be recognized as isolated events in clear weather regions far from urban noise
  - Analysis (JPL,LANL) planned this year

Air Shower Radio Detection by FORTE?



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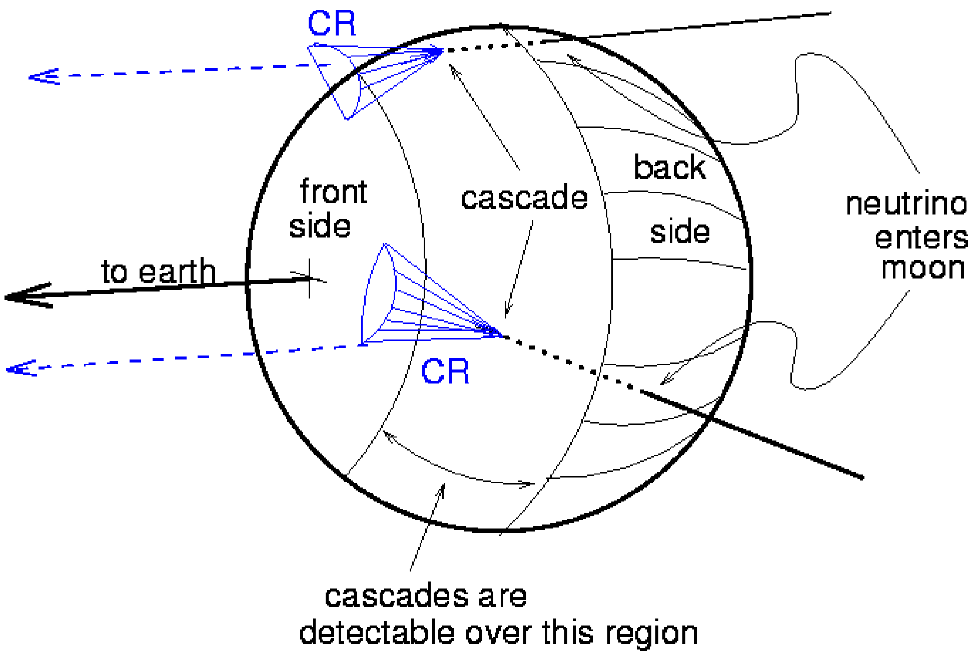
Goldstone Lunar Ultra-High Energy Neutrino Experiment GLUE



- Effective target volume: Antenna beam (~0.3 deg) times ~10 m moon surface layer

===> ~100,000 cubic km!!

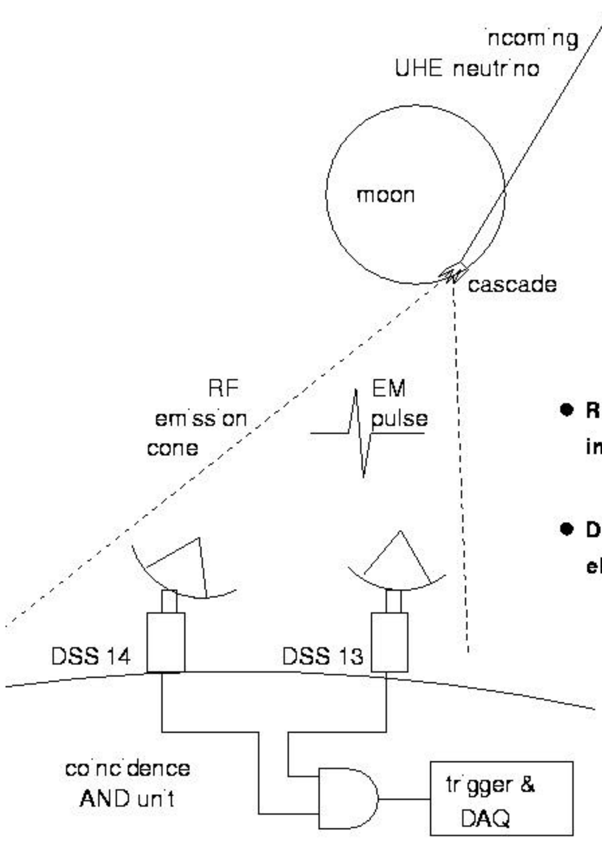
NASA Deep Space Network Radio Astronomy program 2000; ongoing

- At ~100 EeV energies, neutrino interaction length in lunar material is ~60km

- R_{moon} ~ 1740 km, so most detectable interactions are grazing rays, but detection not limited to just limb

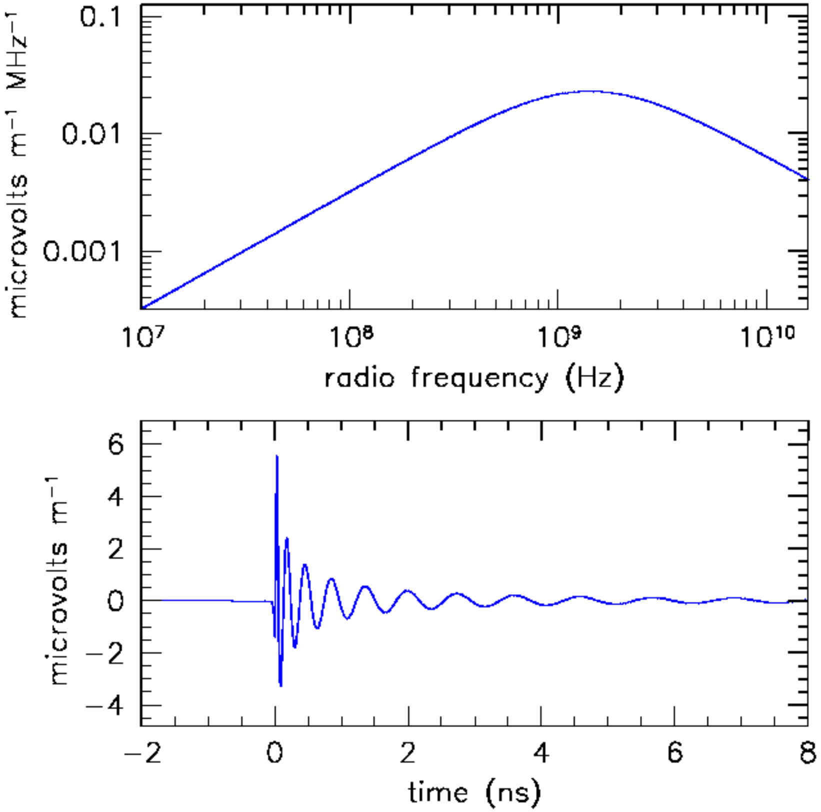
- Refraction of Cherenkov cone at regolith surface “fills in” the pattern, so acceptance solid angle is ~50 times larger than apparent solid angle of moon

GLUE Detection



- **Regolith is transparent in L and S band (10-20cm)**
- **Dual antenna use eliminates terrestrial RFI**

- RF pulse spectrum & shape

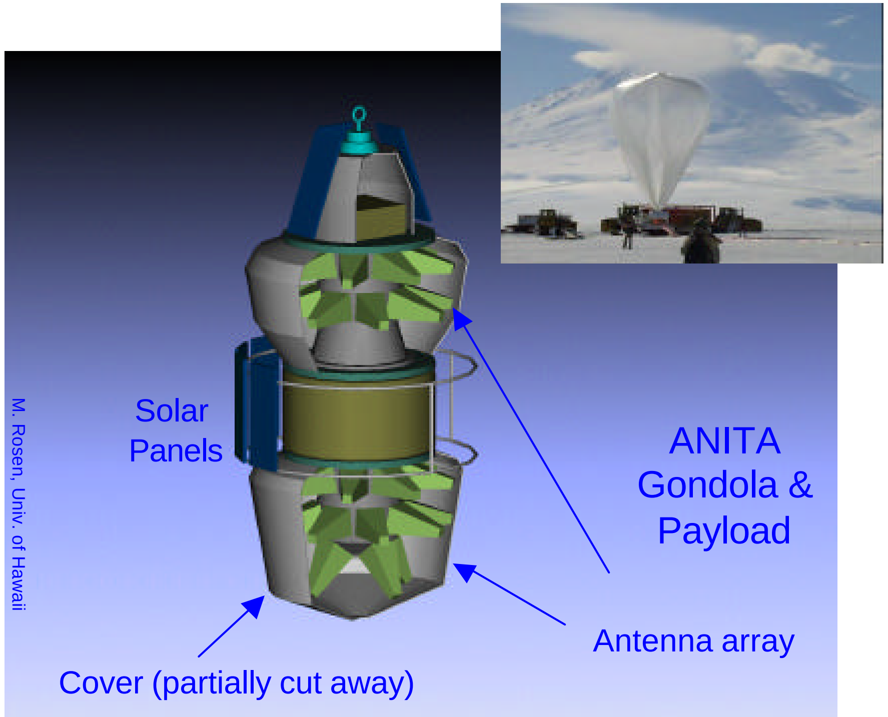


High desert, California

ANtarctic Impulsive Transient Antenna (ANITA)

Antarctic ice:

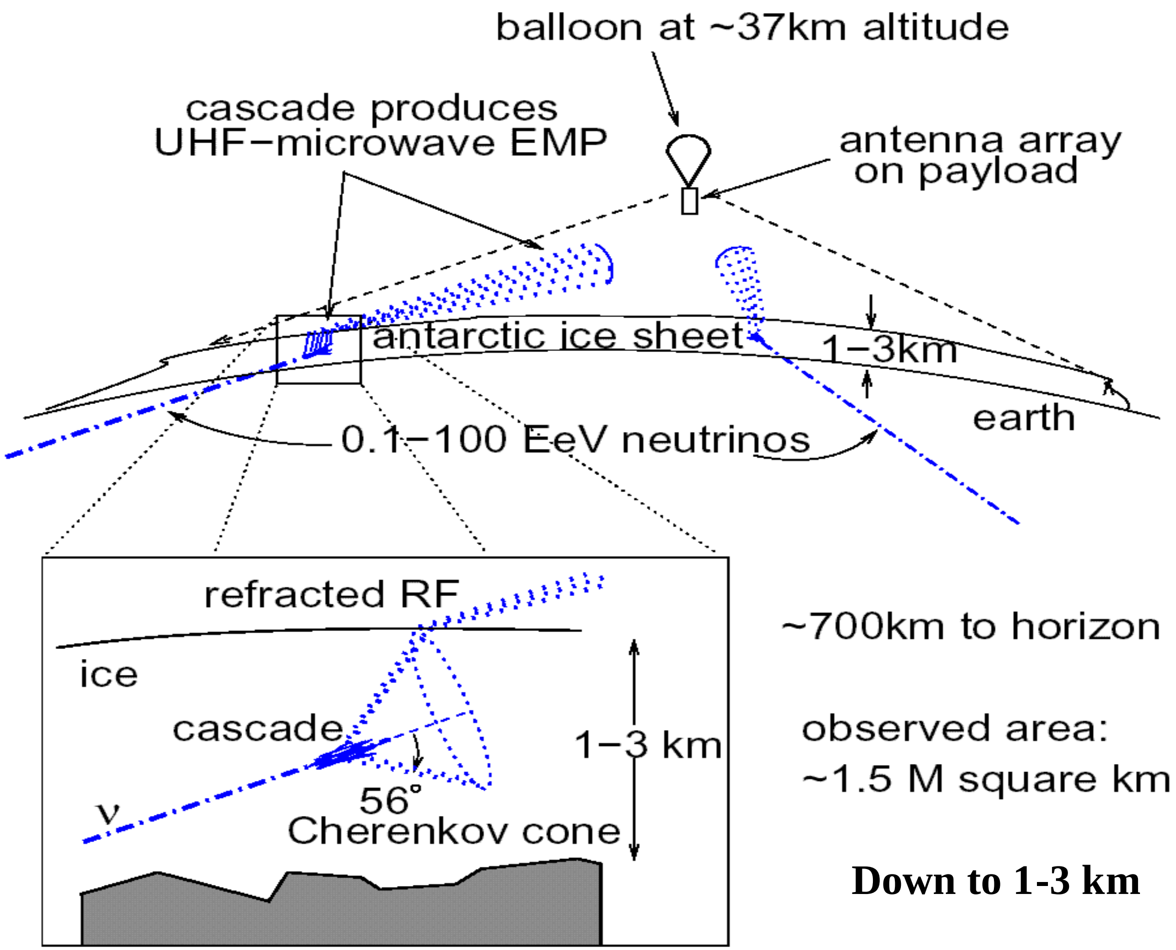
- It does not absorb radio very much - the cold temps help a lot
  - Absorption length = 1000m vs 100m for light
  - Negligible scattering in radio
- There is little unwanted interference from man-made transmitters at balloon altitudes and trajectories
- It preserves linear polarization of Cherenkov light
- There is a lot of it!



600 km radius,
1.1 million km^2

- Launch in 2006 (NASA)

ANITA concept

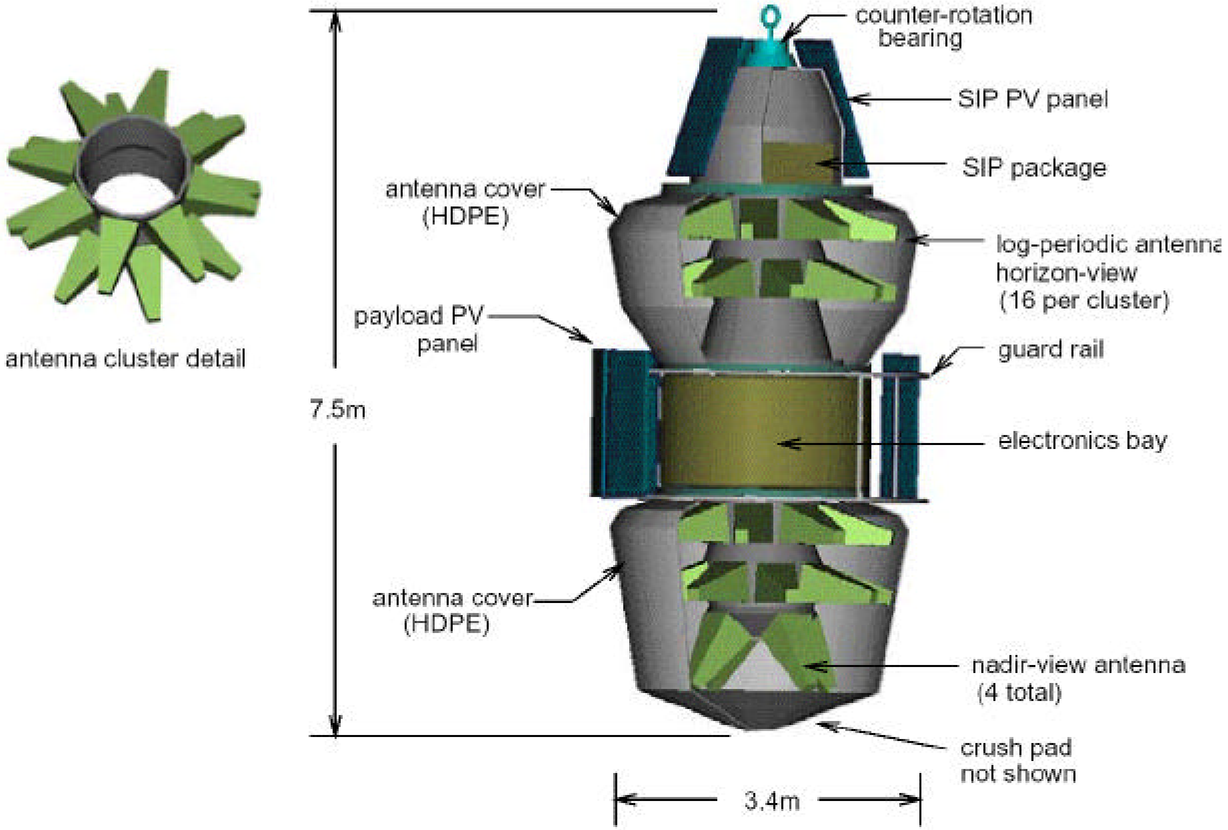


Down to 1-3 km

Antarctic Ice at f<1GHz, T<-20C :

- ~Lossless RF transmission
- Minimal scattering
- largest homogenous, RF-transmissive solid mass in the world (similar to the limb moon but closer)

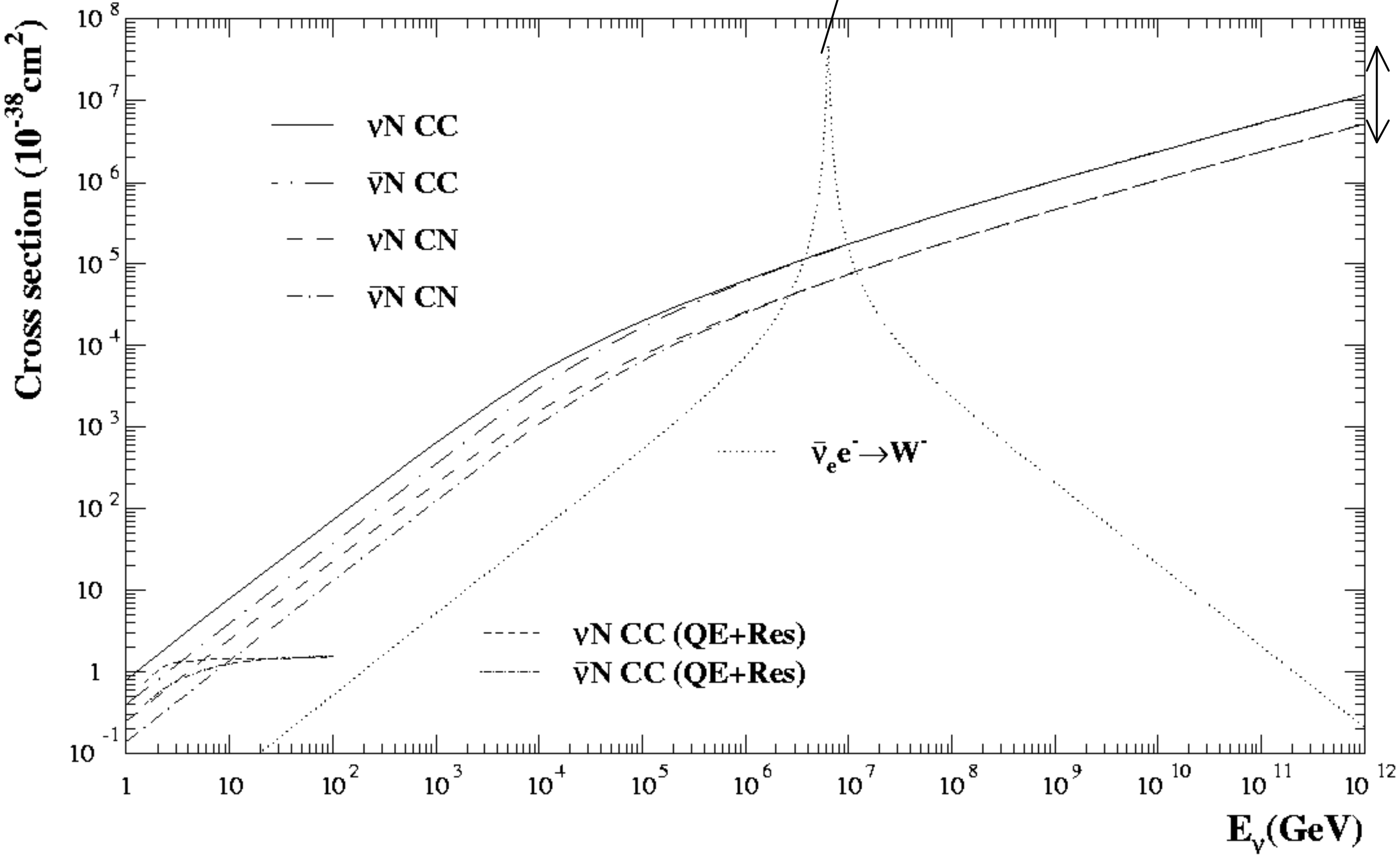
ANITA Payload



- ANITA antennas view ~2pi sr with 60 deg overlapping beams
- Beam intensity gradiometry (ration of overlapping views), interferometry (timing between top and bottom antennas) , polarimetry (signal linearly polarized) used to determine pulse direction & thus original neutrino track orientation

Neutrino Cross Sections

- ν-matter cross sections:



Glashow resonance
× 1000 enhancement

Extrapolation
uncertainty at UHE
× 2.4

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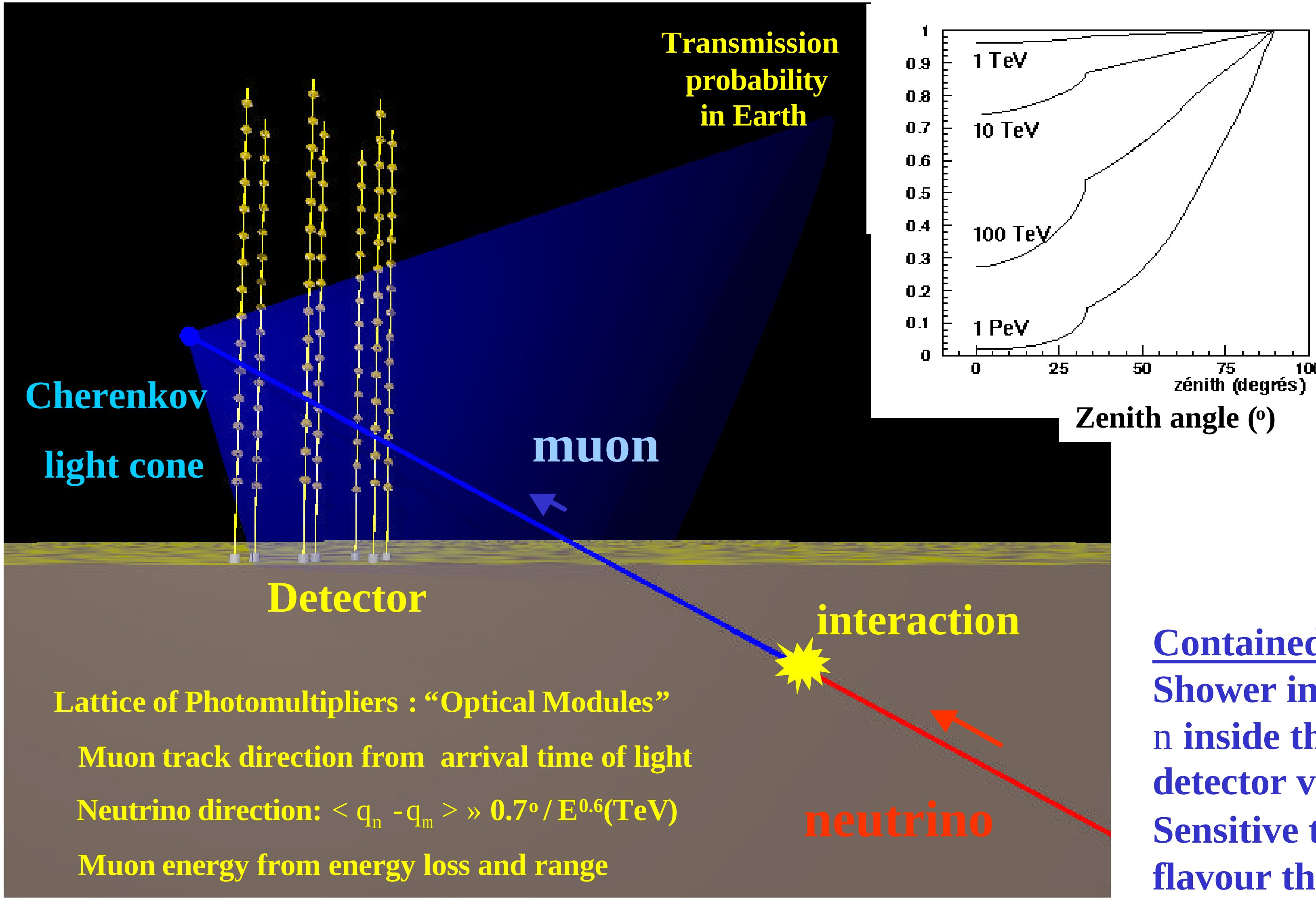
Using Earth as Detector Media



Lattice of Photomultipliers : “Optical Modules”

Muon track direction from arrival time of light

Neutrino direction: $< q_n - q_m >$ » $0.7^o / E^{0.6}$(TeV)

Muon energy from energy loss and range

<u>Contained showers</u>

Shower induced by n inside the detector volume

Sensitive to other n flavour than n_m

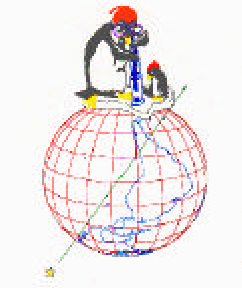
Antares

Neutrinos around PeV
Mediterranean Sea

NEMO
NESTOR

AMANDA & ICECUBE

probes:	n_e, n_m, n_t	from cosmic sources
energy range:	**10^{11}-10^{21} eV**	plus MeV supernova $\bar{\nu}_e$'s



AMANDA:

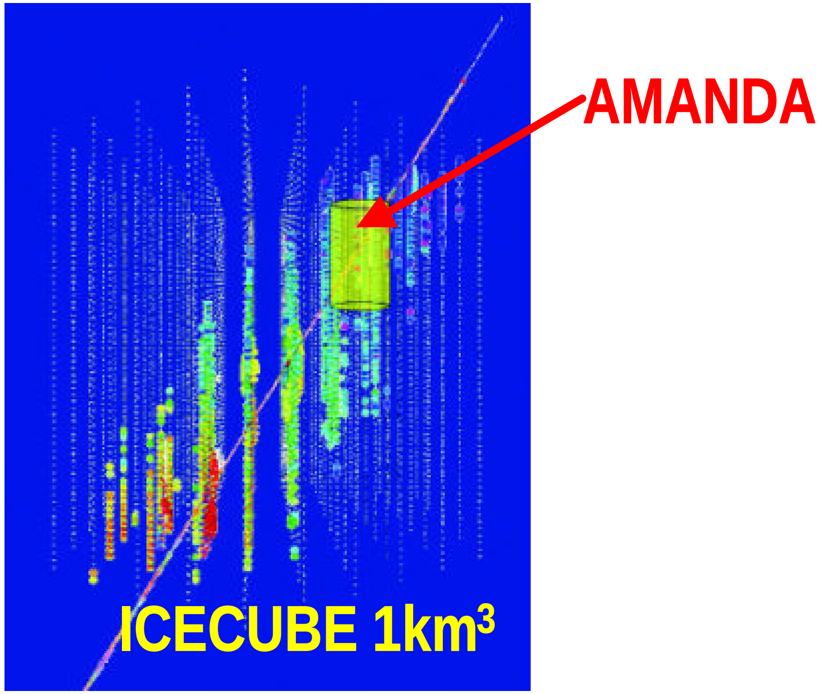
data taking: 1997-X

(will be part of ICECUBE)

ICECUBE:

construction: 2004-2010

data taking: 2005 –2020?

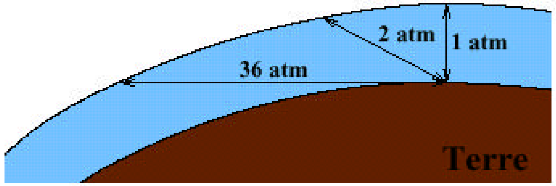


...at the geographical South Pole, Amundsen-Scott Station, Antarctica

Using Horizontal Air Showers

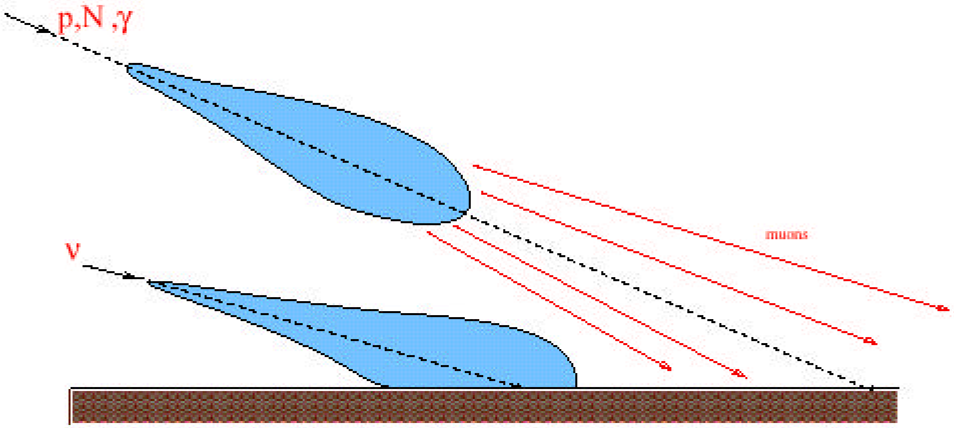
Atmosphere: 1000g/cm^2 thick vertically

36000g/cm^2 thick horizontally



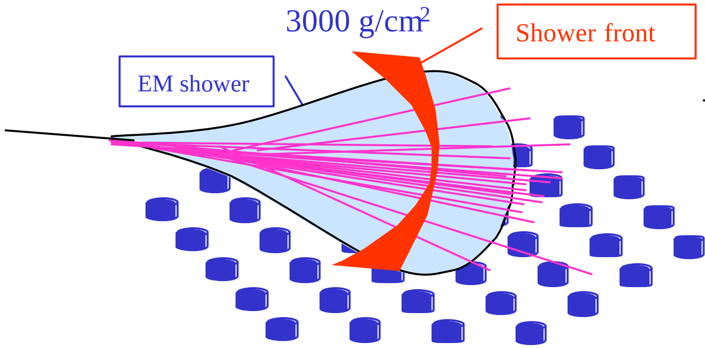
⇒ Look for interactions at deep column densities

i.e. large zenith angles: $75° < \theta < 90°$



Neutrino Air Showers / Hadron Air Showers

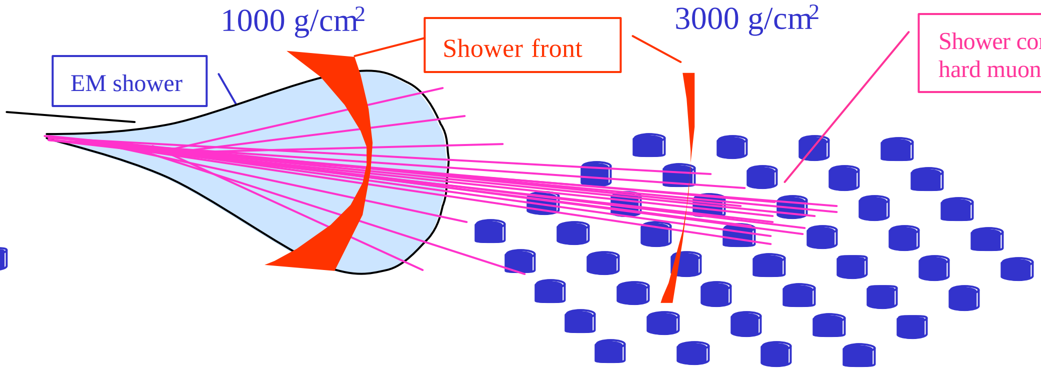
ν : “new” showers



Signal is:

- Few events per year
- EM rich, curved and thick front
- Broad signals

hadrons: “old” showers



Background is:

- Thousands events per year
- EM poor, muon rich, flat and thin front
- Prompt signal

Tau Neutrino Detection

- Principle:
  - Interaction length in the earth ~ 300 km at 10^{18} eV
  - Tau time of flight ~ 50 km at 10^{18} eV
  - 1° below horizon ⇒ 200 km of rock
  - Shower maximum ~10 km after decay

  In practice $85° < \theta_z < 95°$

  AUGER window: 10^{17} to 10^{20} eV

X.Bertou, P.Billoir, O.Deligny, A.Letessier-Selvon

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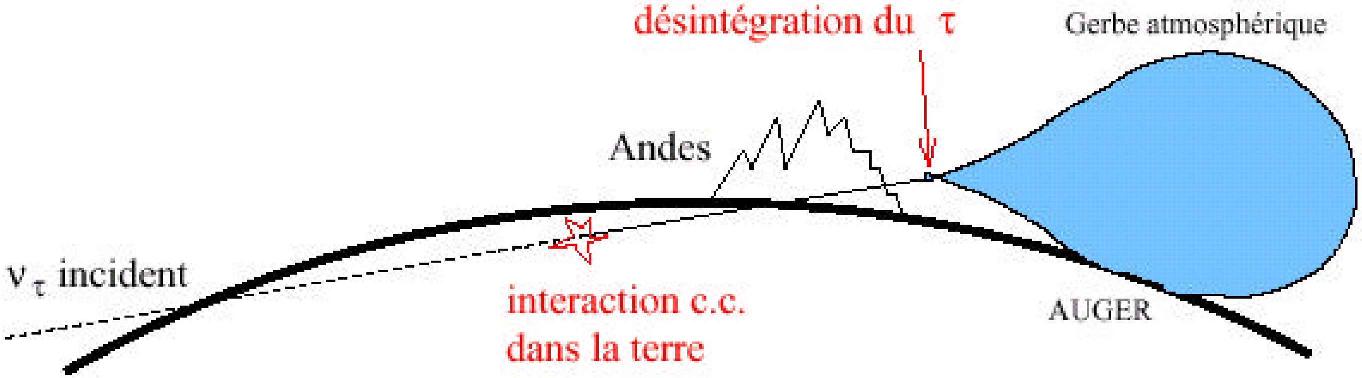
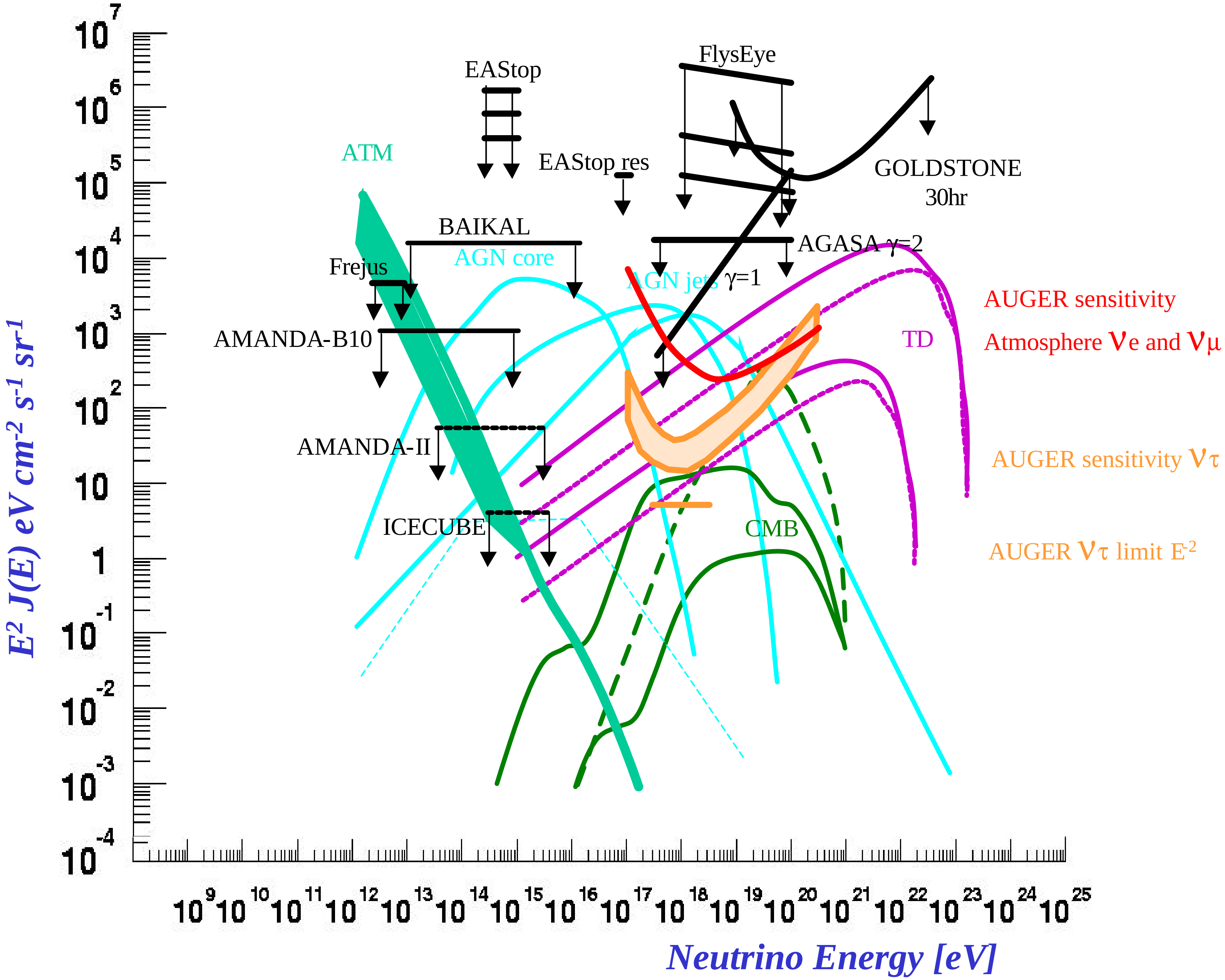


Potential GZK neutrino Detectors

Detector or Experiment	GZK threshold energy(1)	GZK Geometric volume(2)	target density	Effective interaction mass	Effective neutrino target area(3)	Accept-ance solid angle(4)	Aperture	actual or projected livetime/yr	GZK neutrino rate (minimum) (5)	GZK neutrino rate (maximum)
	EeV	km^3	gm/cm^3	km^3 w.e.	km^2	ster	km^2 ster	sec/yr	events per calendar yr	events per calendar yr
Active or completed:										
AGASA(6)	0.3	1000	1.00E-03	1	7.44E-04	2	1.49E-03	3.00E+07	9.8E-03	4.9E-02
AMANDA(7)	0.3	4	0.9	4	2.68E-03	1	2.68E-03	3.00E+07	1.8E-02	8.8E-02
GLUE(8)	300	100,000	2	200,000	1789	0.01	17.89	2.00E+05	1.9E-04	9.5E-04
Fly's Eye(9)	1	500	6.00E-04	0	3.44E-04	2	6.88E-04	3.00E+06	2.9E-04	1.4E-03
HiRes(10)	1	8500	6.00E-04	5	5.85E-03	2	1.17E-02	2.00E+06	3.3E-03	1.6E-02
EAS-TOP(11)	0.3	30	6.00E-04	0	1.34E-05	2	2.68E-05	1.00E+07	3.7E-05	1.9E-04
RICE(12)	0.3	1	0.9	1	6.69E-04	6	4.02E-03	3.00E+06	2.7E-03	1.3E-02
In construction or advanced planning:										
Auger(13)	1	1.50E+04	8.00E-04	12	1.38E-02	2	2.75E-02	3.00E+07	0.12	0.58
EUSO(14)	100	1.00E+06	1.00E-03	1,000	6.0	2	12.04	3.00E+06	1.5E-02	7.6E-02
IceCube(15)	0.3	40	0.9	36	2.68E-02	1	2.68E-02	3.00E+07	0.19	0.94
Telescope Array	1	3.00E+04	1.00E-03	30	3.44E-02	2	6.88E-02	2.00E+06	1.9E-02	9.6E-02
Proposed, pre-proposal, or conceptual										
OWL(16)	100	3.00E+06	1.00E-03	3,000	18.1	2	36.13	3.00E+06	4.6E-02	0.23
ANITA(17)	0.3	1.00E+06	0.9	900,000	669	0.01	6.69	2.50E+06	3.7	18.4
SALSA(18)	0.3	30	2.2	66	4.91E-02	6	0.29	3.00E+07	2.1	10.4
SuperRICE(19)	10	100	0.9	90	2.37E-01	6	1.42	3.00E+07	0.81	4.0

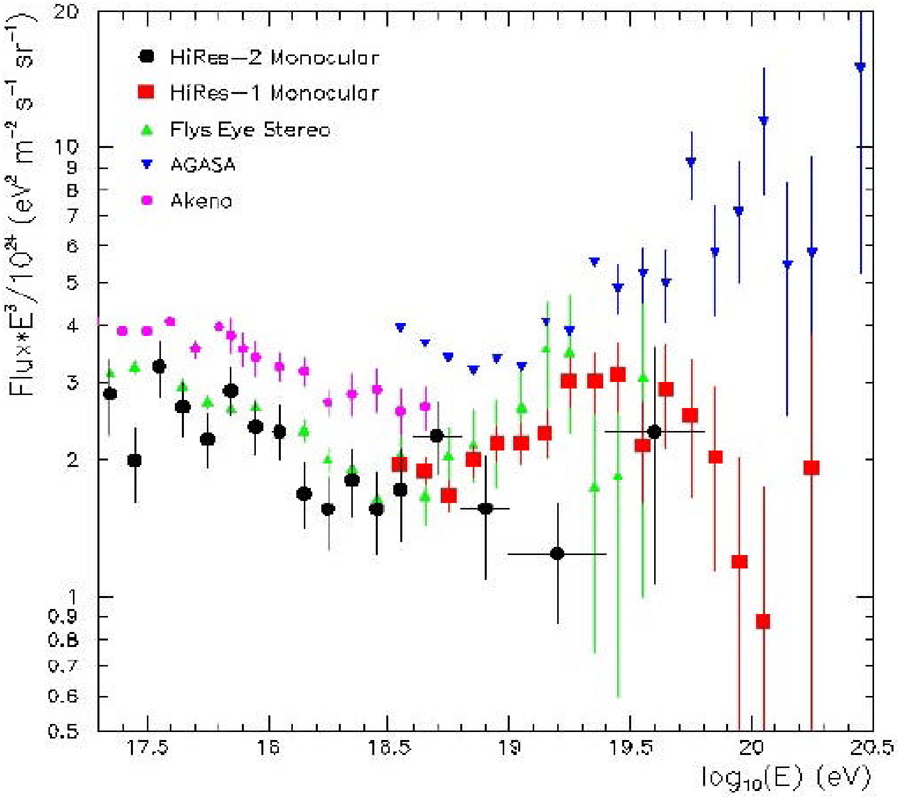
Tiina Suomijärvi, ISAPP 2003

Limits


$E^2 J(E)\ eV\ cm^{-2}\ s^{-1}\ sr^{-1}$
Neutrino Energy [eV]
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21} 10^{22} 10^{23} 10^{24} 10^{25}
FlysEye
EAStop
ATM
EAStop res
GOLDSTONE
30hr
BAIKAL
AGN core
AGASA γ=2
Frejus
AGN jets γ=1
AUGER sensitivity
Atmosphere νe and νμ
TD
AMANDA-B10
AMANDA-II
AUGER sensitivity ντ
ICECUBE
CMB
AUGER ντ limit E^{-2}

Future

Work in progress



Differences observed between ground arrays and fluorescence telescopes
Better atmospheric monitoring and modeling !

Differences in simulations, hadronic cross sections !

Primary identification techniques

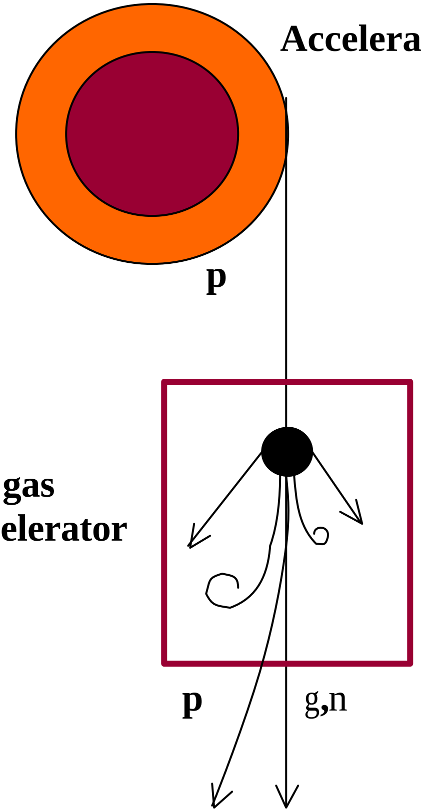
GZK cutoff or not ?

Look for antimatter, dark matter

Develop new detection techniques

Radiodetection :

High energy neutrinos



Accelerator

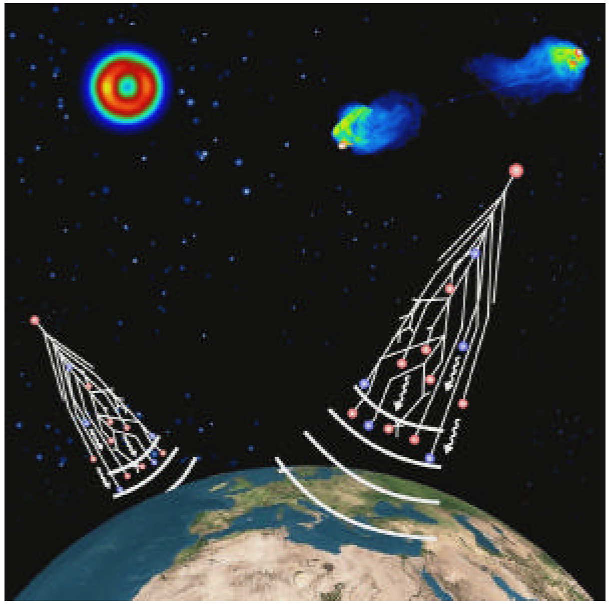
p

Target:
Radiation and gas
around the accelerator

Magnetic field

p

g,n



Correlation of different observations !

Multi-messenger analysis