Moon Base: Scientific Opportunities for Astroparticle Physics

Piero Spillantini
Univ. and INFN, Firenze, Italy

Response to the *Cosmic Vision 2015-2025* ESA call

LUNAR OBSERVATORY FOR COSMIC RAY PHYSICS

We propose the ambitious idea of observing Primary Cosmic Rays (PCR) and High Energy Gamma Ray (HEGR) from the Moon, discussing its major scientific and technological advantages as well as the exceptional opportunity for an incomparable breakthrough in this frontier science. There are some important measurements that can be conducted on the Moon surface:

……………………………………………………………………………………………………

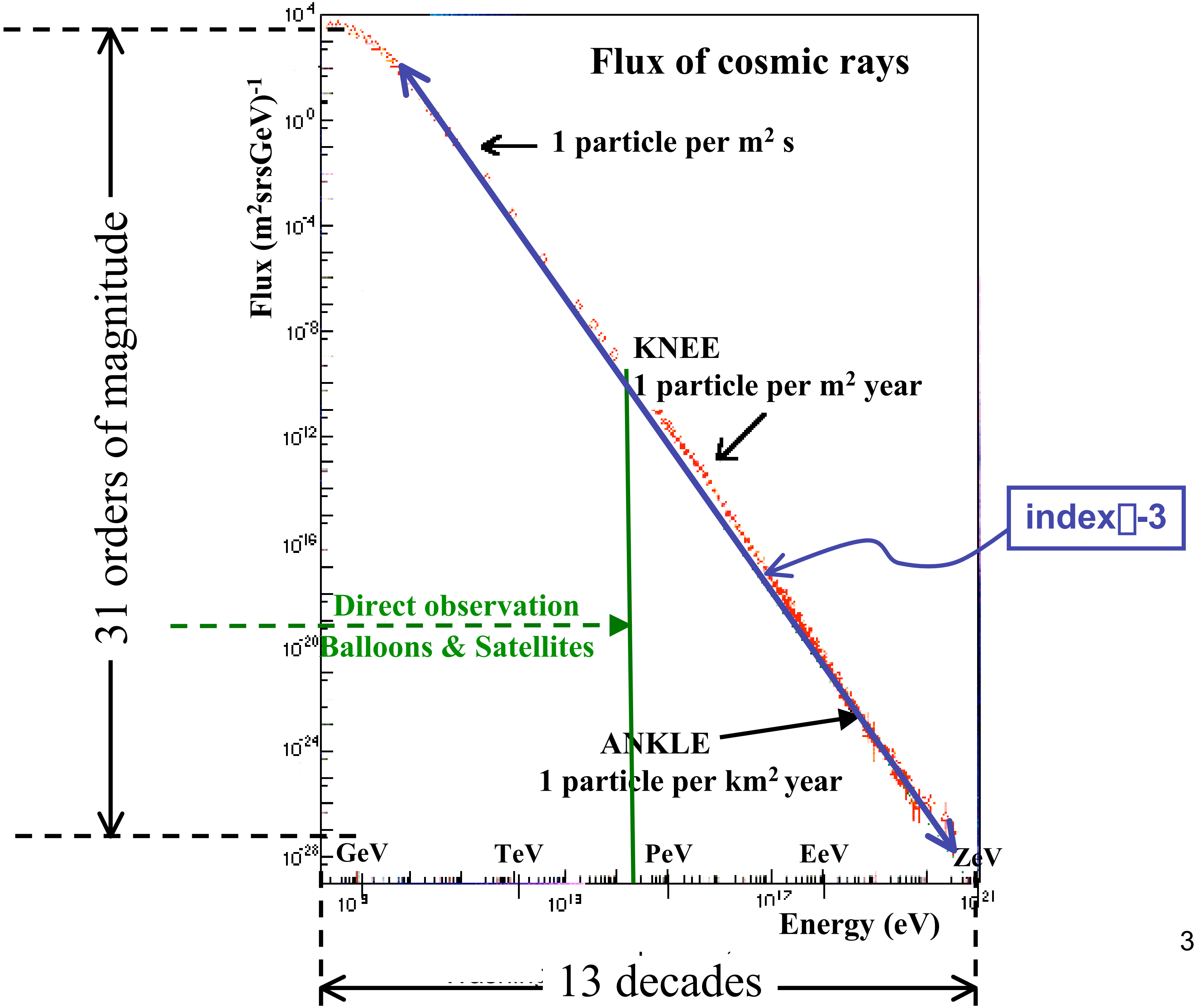
Each of these measurements could take advantage from, and be the target of, a specific project for a dedicated Moon-based experimental facility. However, the **combination of all of them in a single base** represents the very challenging and really advanced program, because of the synergy of different detection systems and measurements.

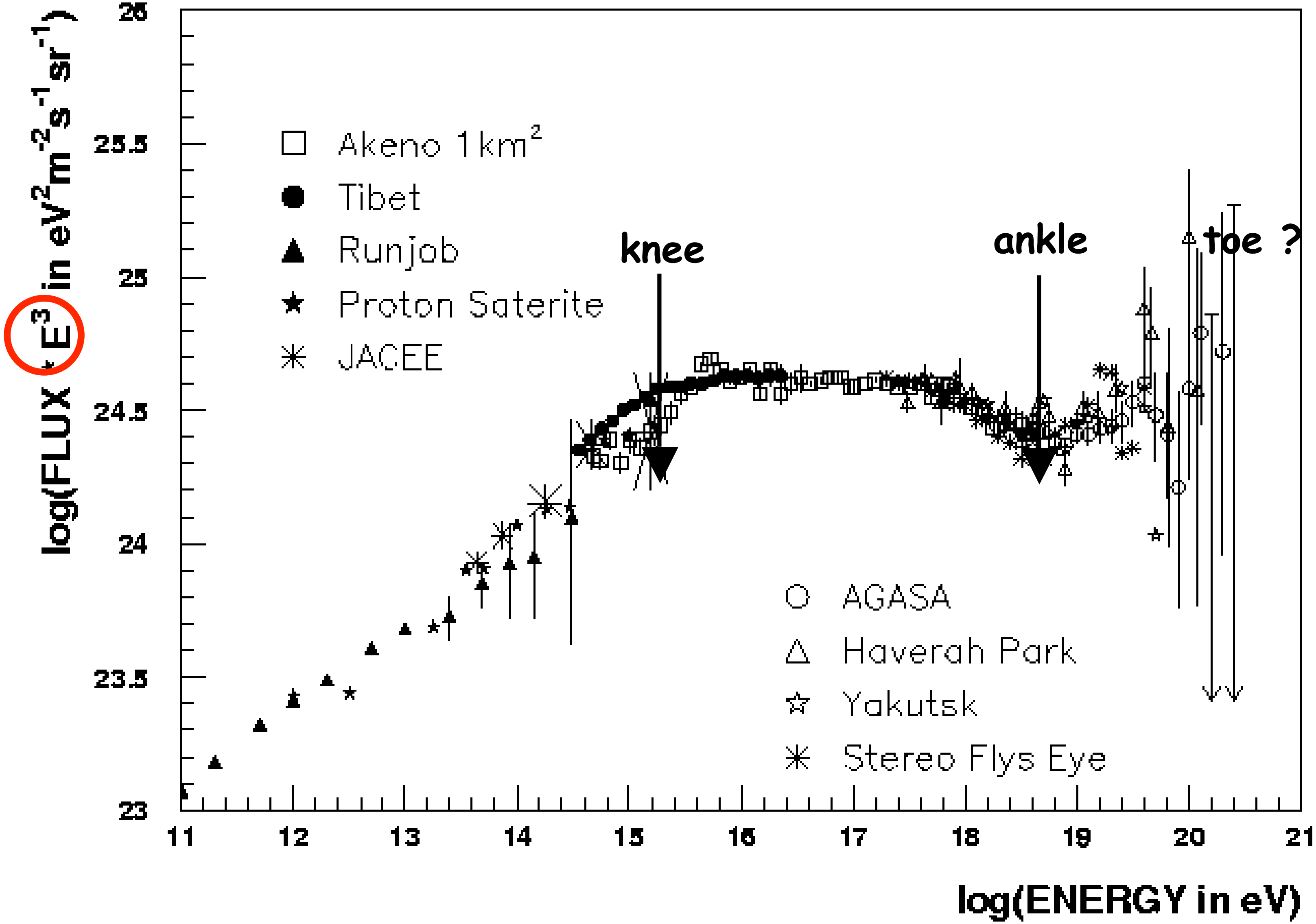
……

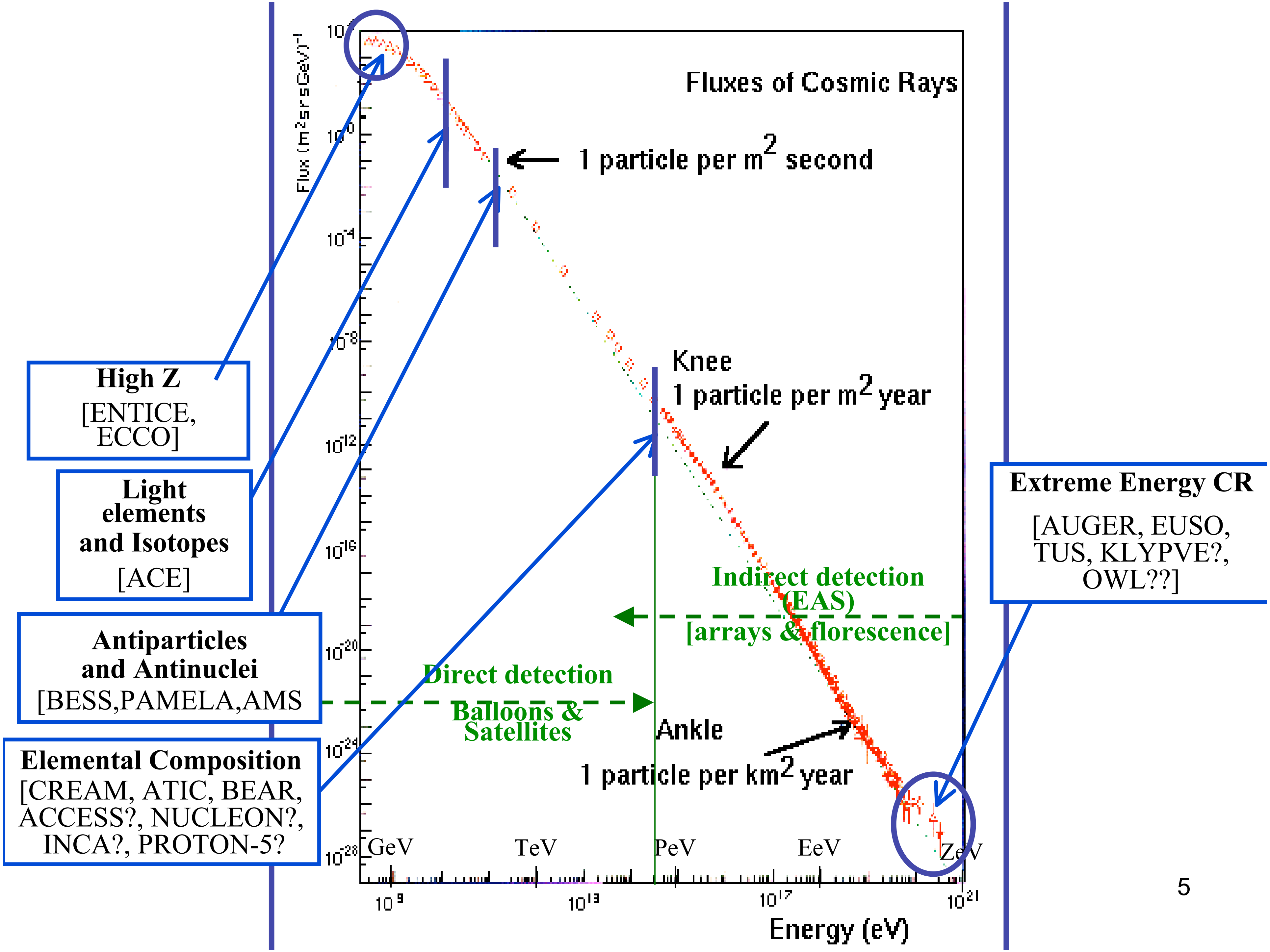
The observation of PCR and HEGR on the Moon will imply a unique opportunity for strong developments of technologies for extraterrestrial applications (building structures on a low gravity and inhospitable surface, use of local materials, robotic operations and equipments – even mobile – robotic handling and assembly, deployable structures, development of Earth-Moon carriers and Lunar landers, etc.), giving Europe further fields of excellence.

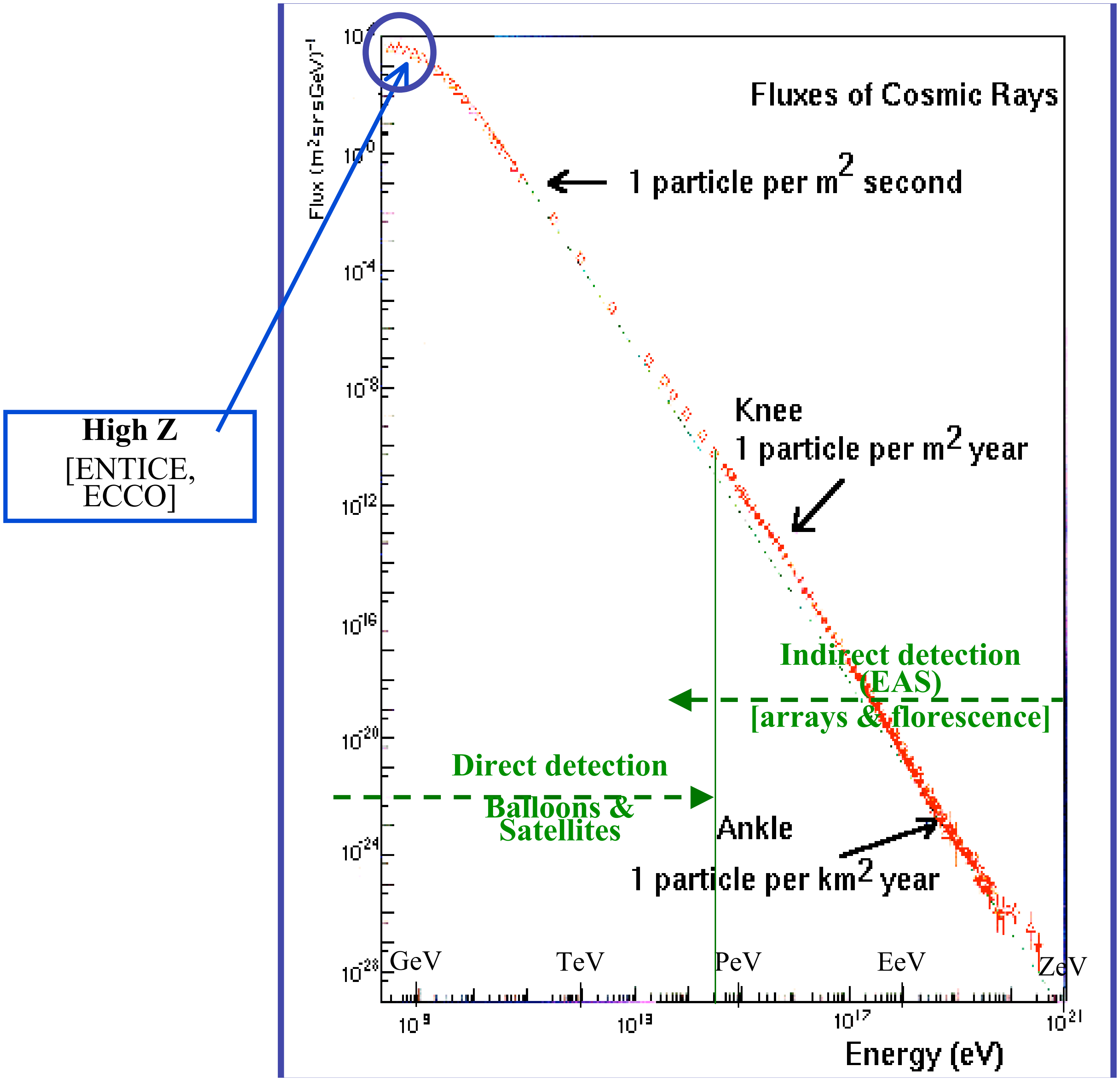
Pace Emanuele, University and INFN, Florence, Italy
Spillantini Piero, University and INFN, Florence, Italy

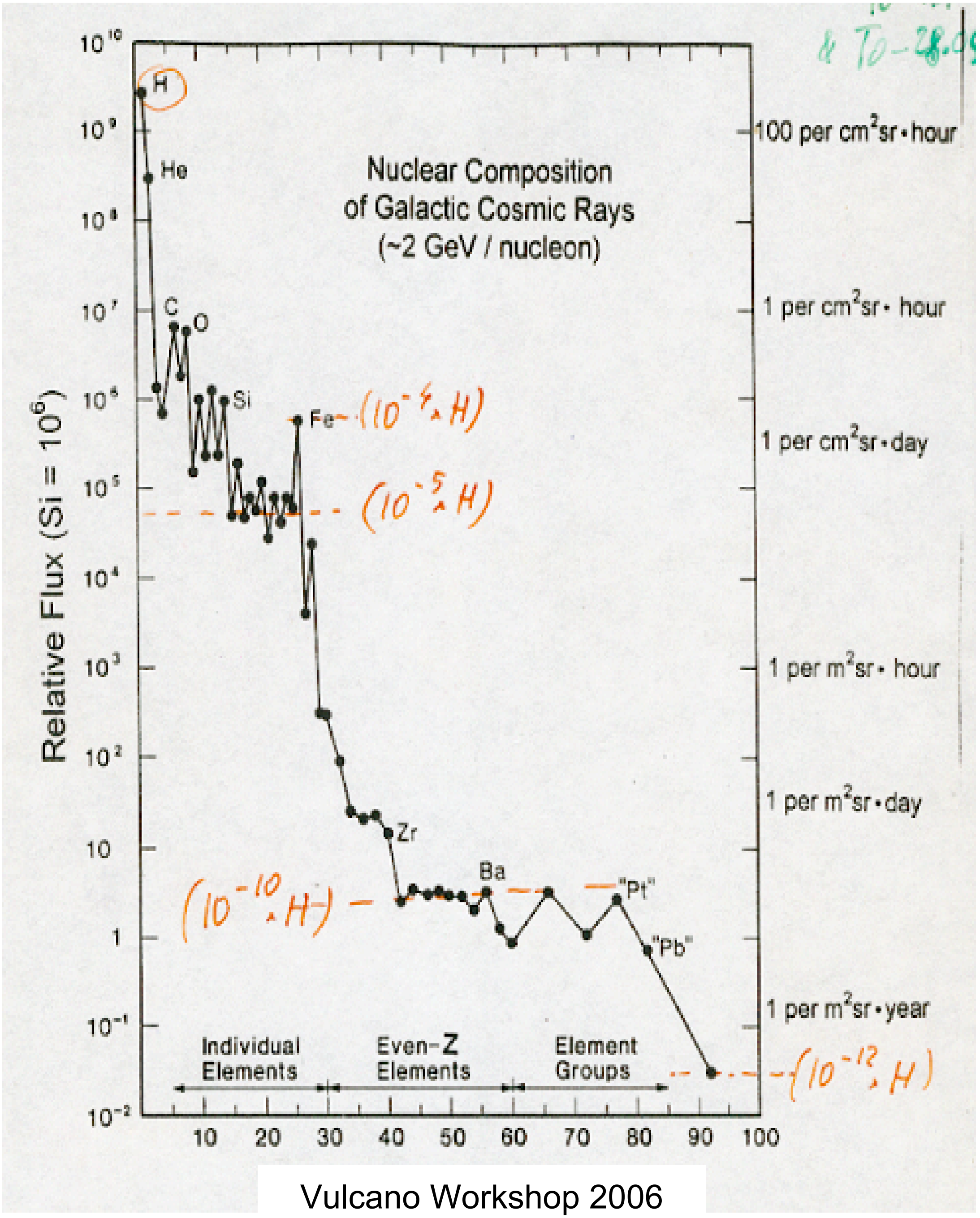
Florence, 30 May 2004

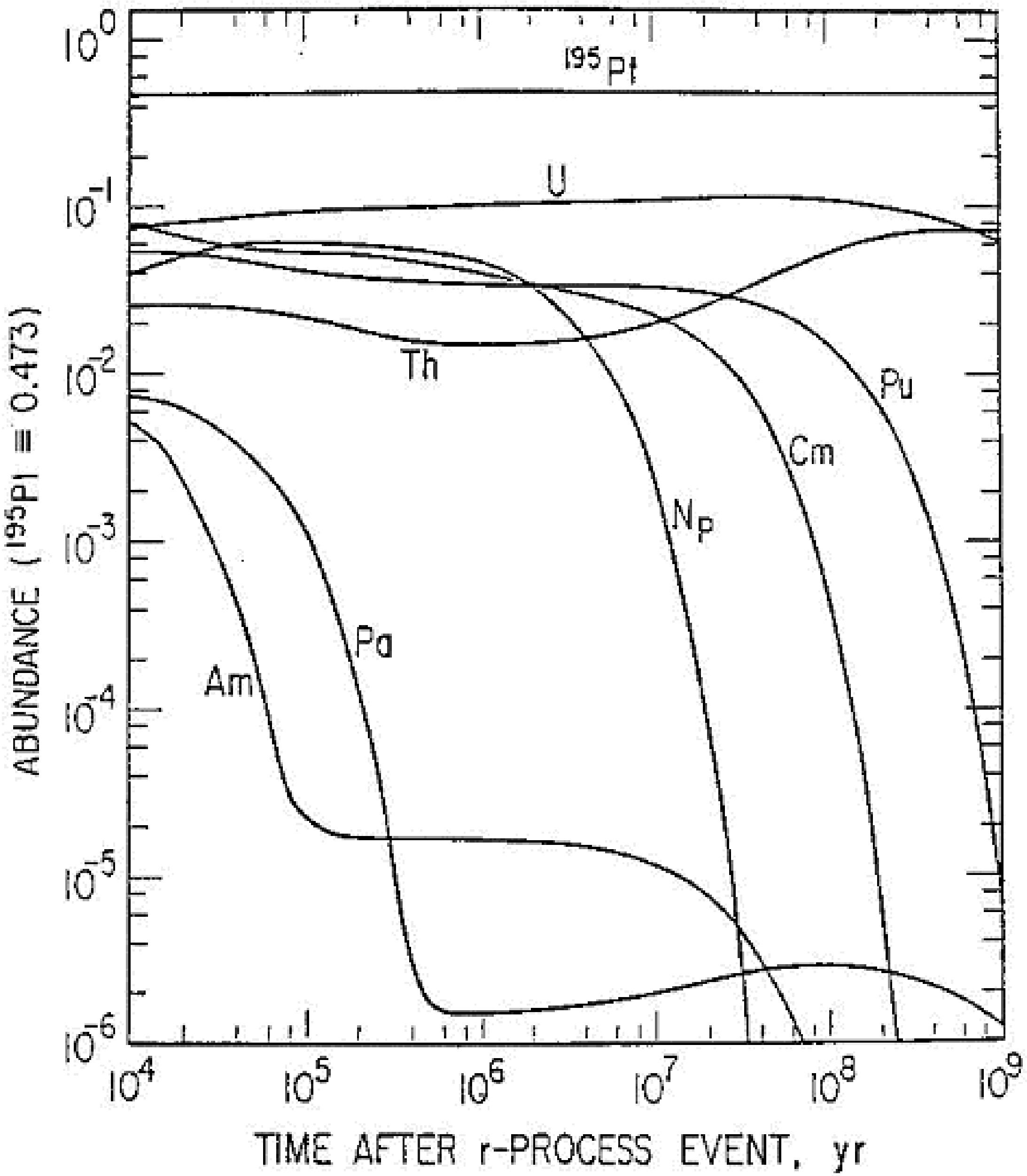

Flux of cosmic rays
1 particle per m² s
KNEE
1 particle per m² year
index-3
Direct observation
Balloons & Satellites
ANKLE
1 particle per km² year
Flux (m²srsGeV)⁻¹
31 orders of magnitude
GeV
TeV
PeV
EeV
ZeV
Energy (eV)
13 decades


log(FLUX * E^3 in eV^2m^-2s^-1sr^-1)
Akeno 1km²
Tibet
Runjob
Proton Saterite
JACEE
knee
ankle
toe ?
AGASA
Haverah Park
Yakutsk
Stereo Flys Eye
23
23.5
24
24.5
25
25.5
26
11
12
13
14
15
16
17
18
19
20
21
log(ENERGY in eV)


Fluxes of Cosmic Rays
Flux (m² sr s GeV)⁻¹
Energy (eV)
1 particle per m² second
Knee
1 particle per m² year
Ankle
1 particle per km² year
GeV
TeV
PeV
EeV
ZeV
Indirect detection (EAS)
[arrays & florescence]
Direct detection
Balloons & Satellites
High Z
[ENTICE, ECCO]
Light elements and Isotopes
[ACE]
Antiparticles and Antinuclei
[BESS,PAMELA,AMS
Elemental Composition
[CREAM, ATIC, BEAR, ACCESS?, NUCLEON?, INCA?, PROTON-5?
Extreme Energy CR
[AUGER, EUSO, TUS, KLYPVE?, OWL??]


High Z
[ENTICE, ECCO]
Fluxes of Cosmic Rays
1 particle per m2 second
Knee
1 particle per m2 year
Indirect detection
(EAS)
[arrays & florescence]
Direct detection
Balloons &
Satellites
Ankle
1 particle per km2 year
GeV
TeV
PeV
EeV
ZeV
Flux (m2 sr s GeV)-1
Energy (eV)

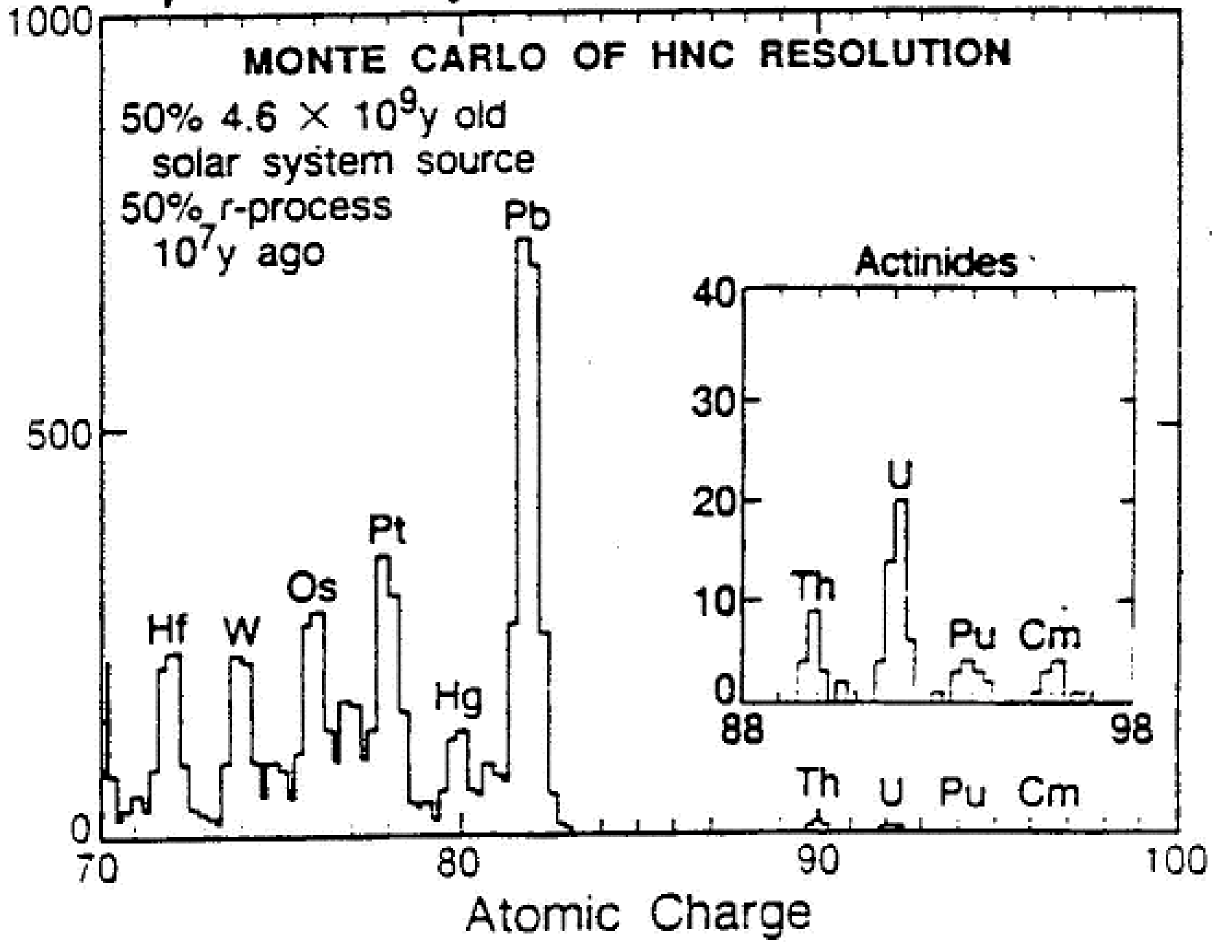

Nuclear Composition
of Galactic Cosmic Rays
(~2 GeV / nucleon)
Relative Flux (Si = 10^6)
H
He
C
O
Si
Fe
Zr
Ba
"Pt"
"Pb"
100 per cm²sr • hour
1 per cm²sr • hour
1 per cm²sr • day
1 per m²sr • hour
1 per m²sr • day
1 per m²sr • year
Individual Elements
Even-Z Elements
Element Groups



ABUNDANCE (195Pt ≡ 0.473)
TIME AFTER r-PROCESS EVENT, yr
195Pt
U
Th
Pu
Cm
Np
Pa
Am
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^4
10^5
10^6
10^7
10^8
10^9

Heavy Nuclei Collector (HNC) [30m^2] planned for 'Freedom' Space Station

planned for Space Stations



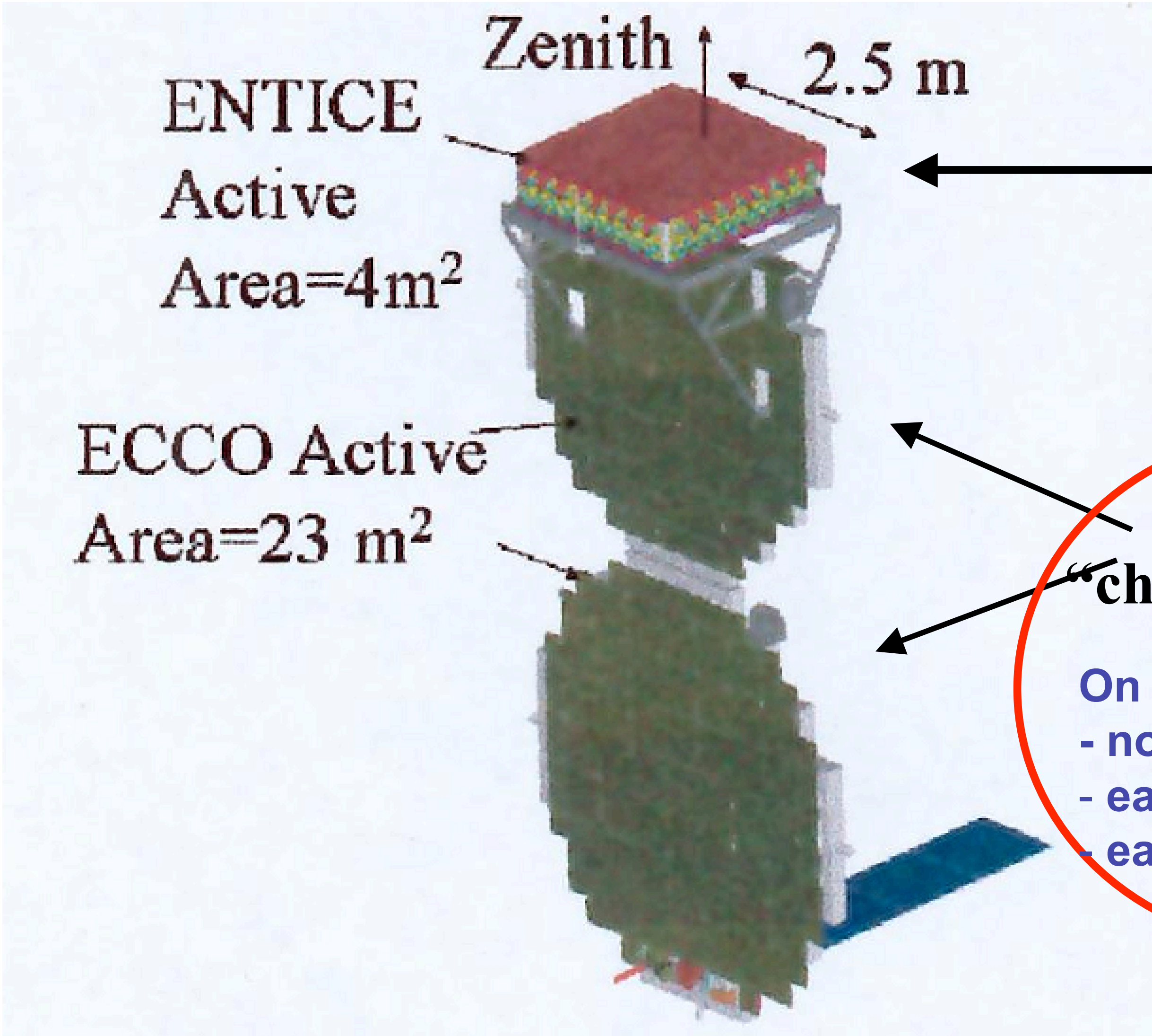
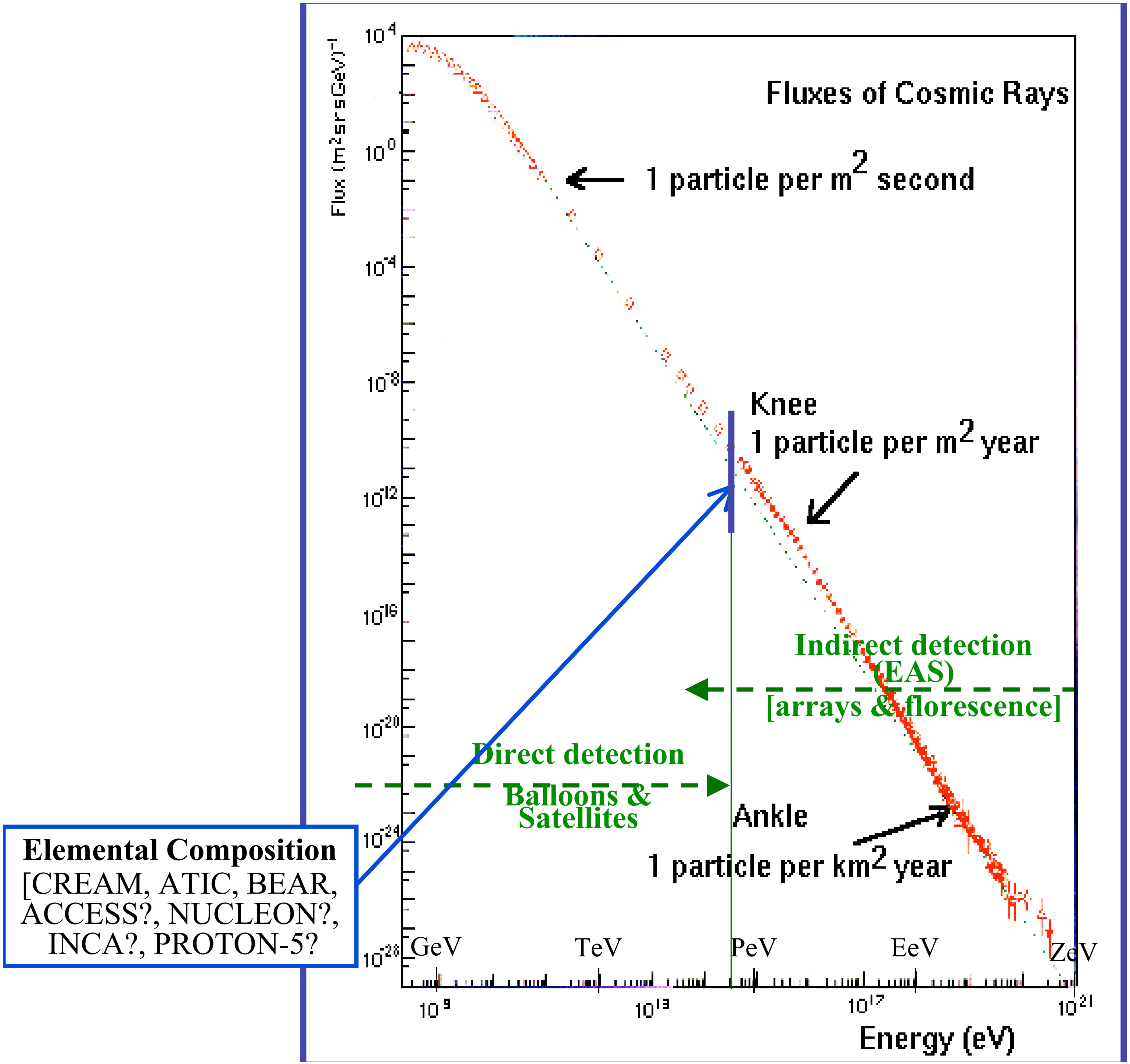


Figure 1—HNX is shown in its deployed configuration.

Elettronic device

Etching of "charged" glasses

On the Moon:
- no magnetic field
- easily deploied
- easily recovered



Fluxes of Cosmic Rays
Flux (m²sr s GeV)⁻¹
1 particle per m² second
Knee
1 particle per m² year
Indirect detection
(EAS)
[arrays & florescence]
Direct detection
Balloons &
Satellites
Ankle
1 particle per km² year
GeV
TeV
PeV
EeV
ZeV
Energy (eV)
Elemental Composition
[CREAM, ATIC, BEAR,
ACCESS?, NUCLEON?,
INCA?, PROTON-5?

The KNEE region
(3 x 10^{15} eV)

Border energy between space (balloon and satellite borne) and ground based experiments.

but also

Border energy between different acceleration processes of cosmic rays in the Universe.

‘Standard’ model of the acceleration of cosmic rays in supernovae

First order Fermi acceleration:

+ limits in energy:

$E_{limit} = BLZ = 3 \times 10^{14} \times Z$ eV

B = magnetic field

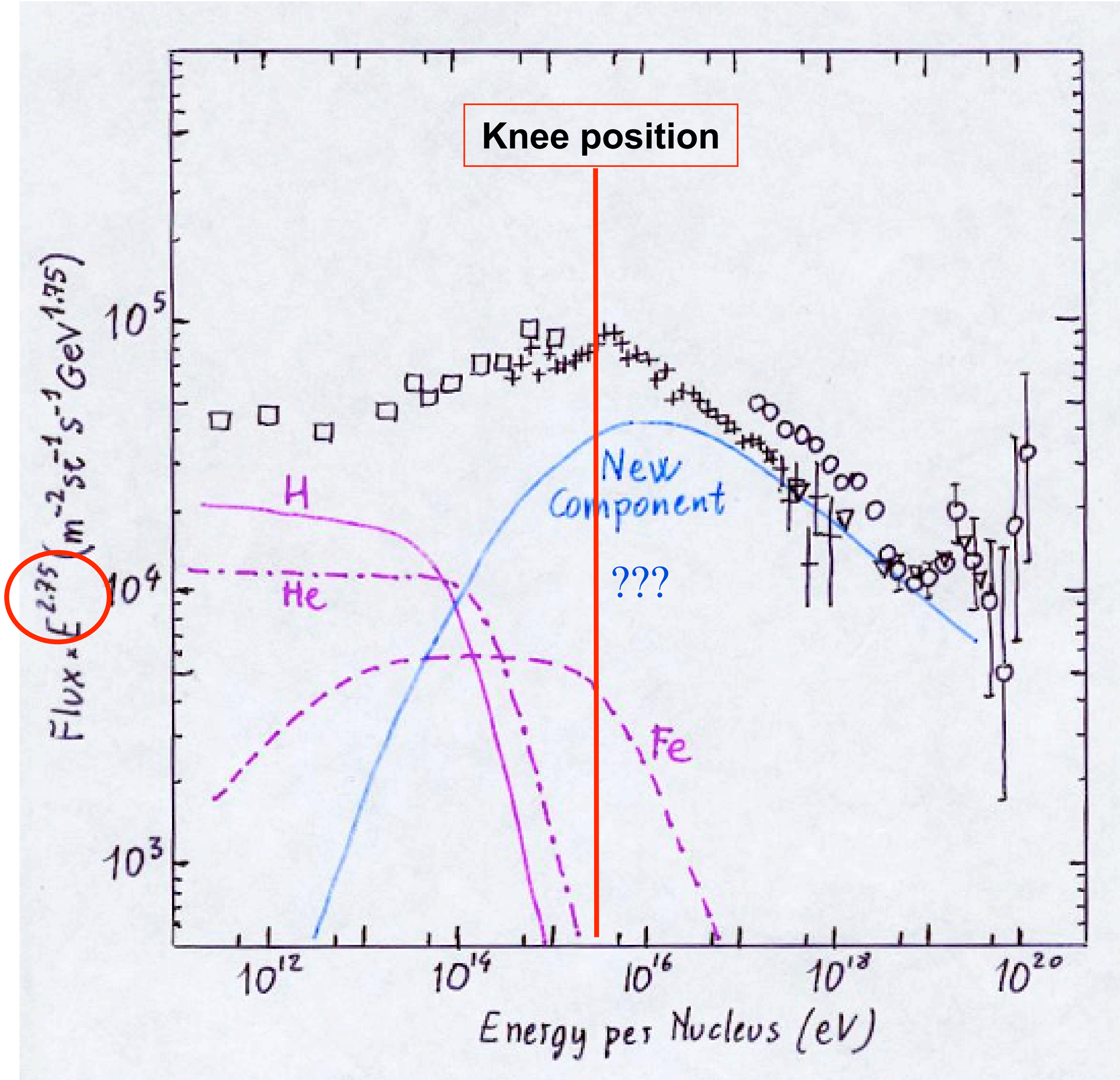
L = characteristic dimension of the magnetic turbolence

Z = charge of the nucleus

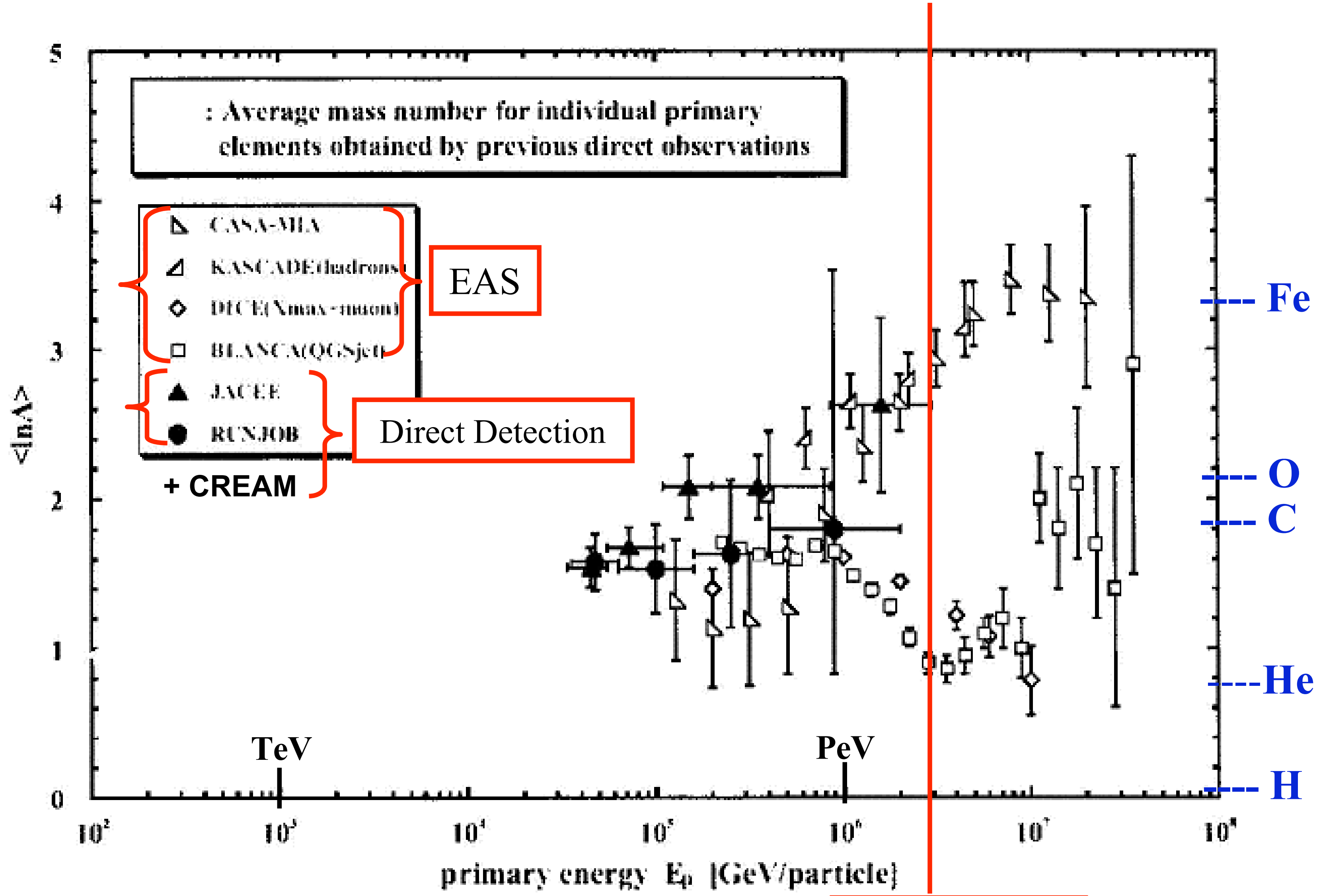
+ chemical composition change at $E > \sim 10^{14}$ eV

+ power index of spectra changes

+ isotropy of the fluxes



Knee position
New
Component
???
H
He
Fe
10^5
10^4
10^3
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
Flux $\times E^{2.75}$ $(m^{-2} sr^{-1} s^{-1} GeV^{1.75})$
Energy per Nucleus (eV)

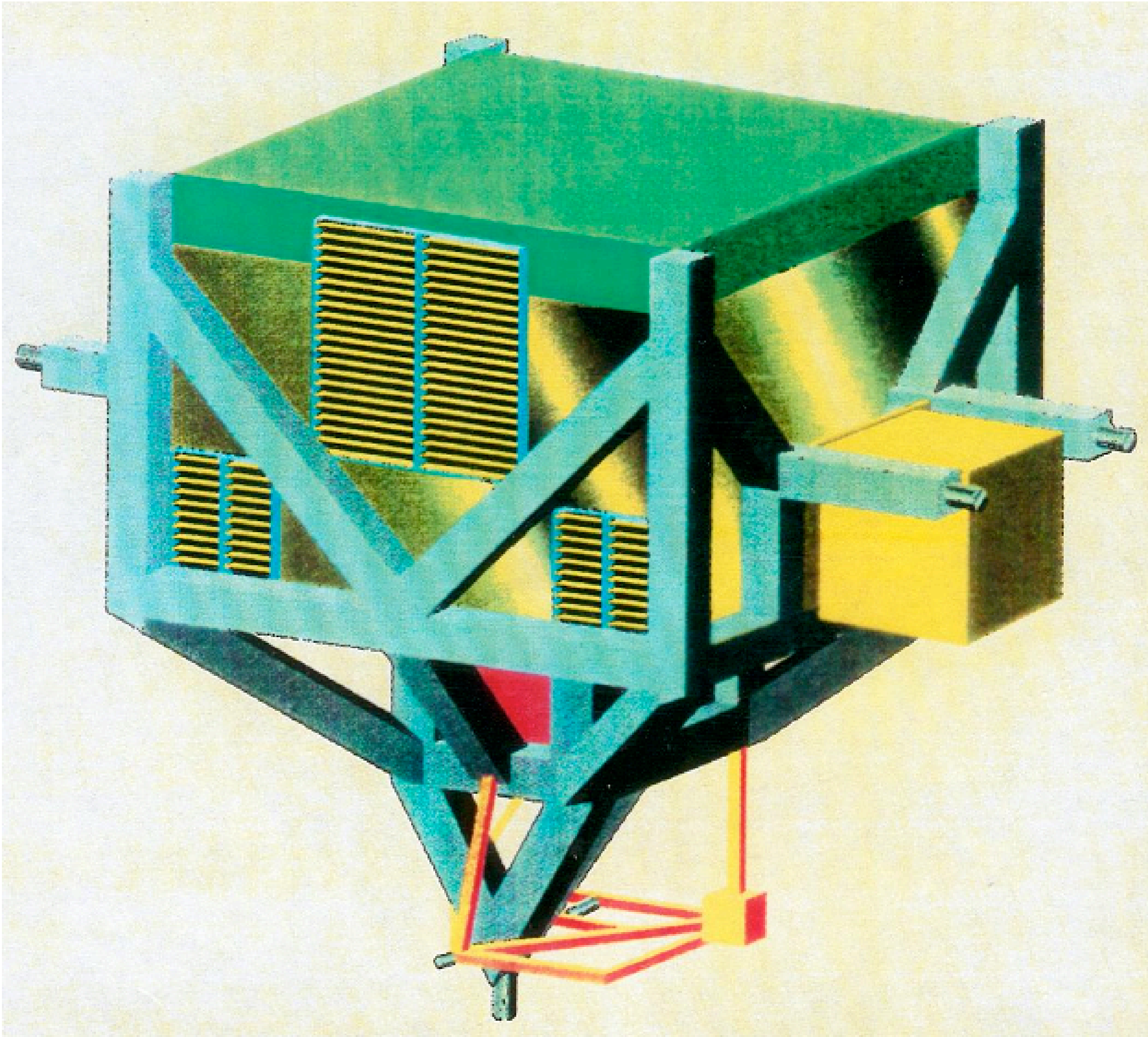


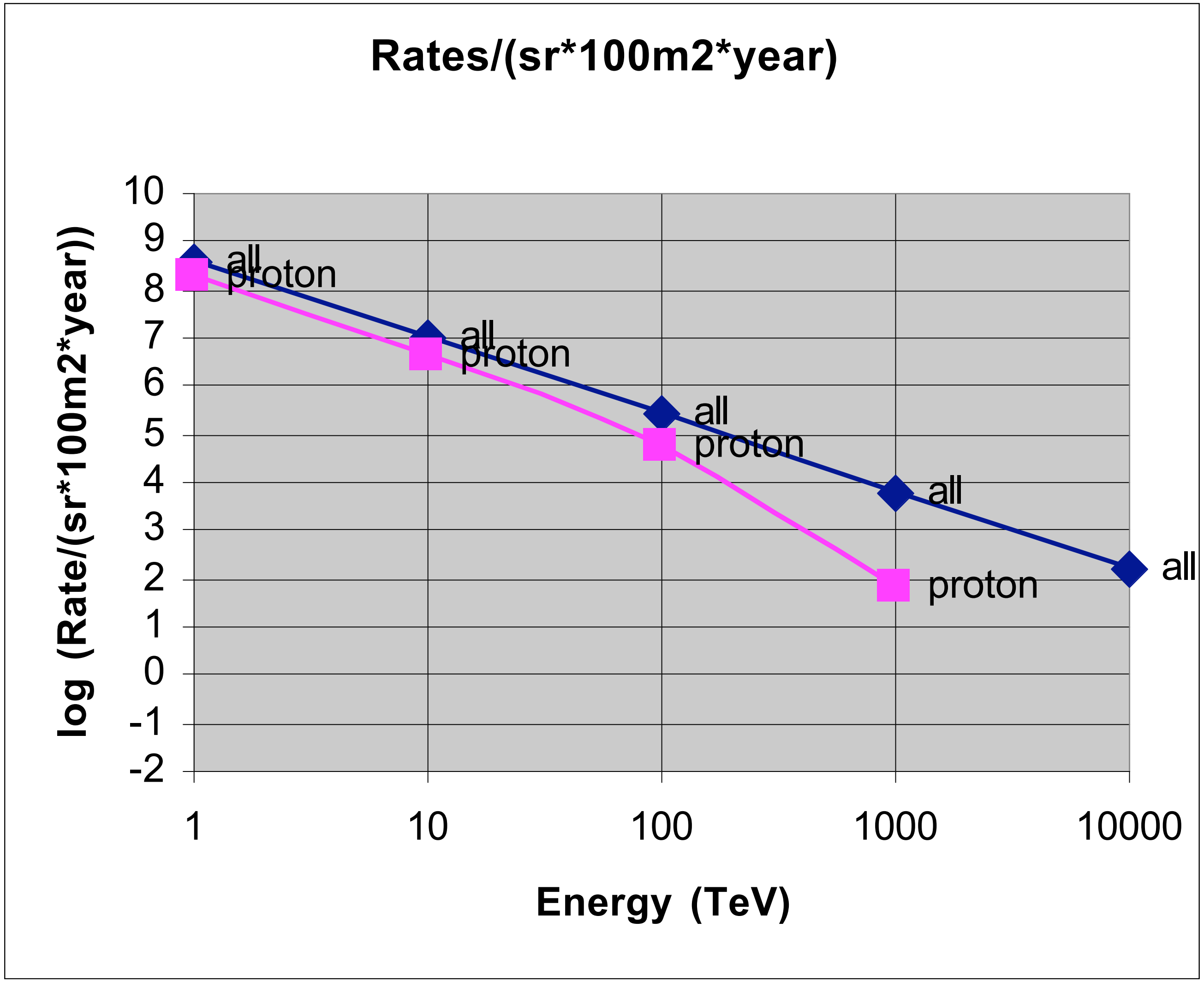
Knee position

Fig. 3. Energy dependence of average mass number of primary cosmic-ray particles.

ACCESS

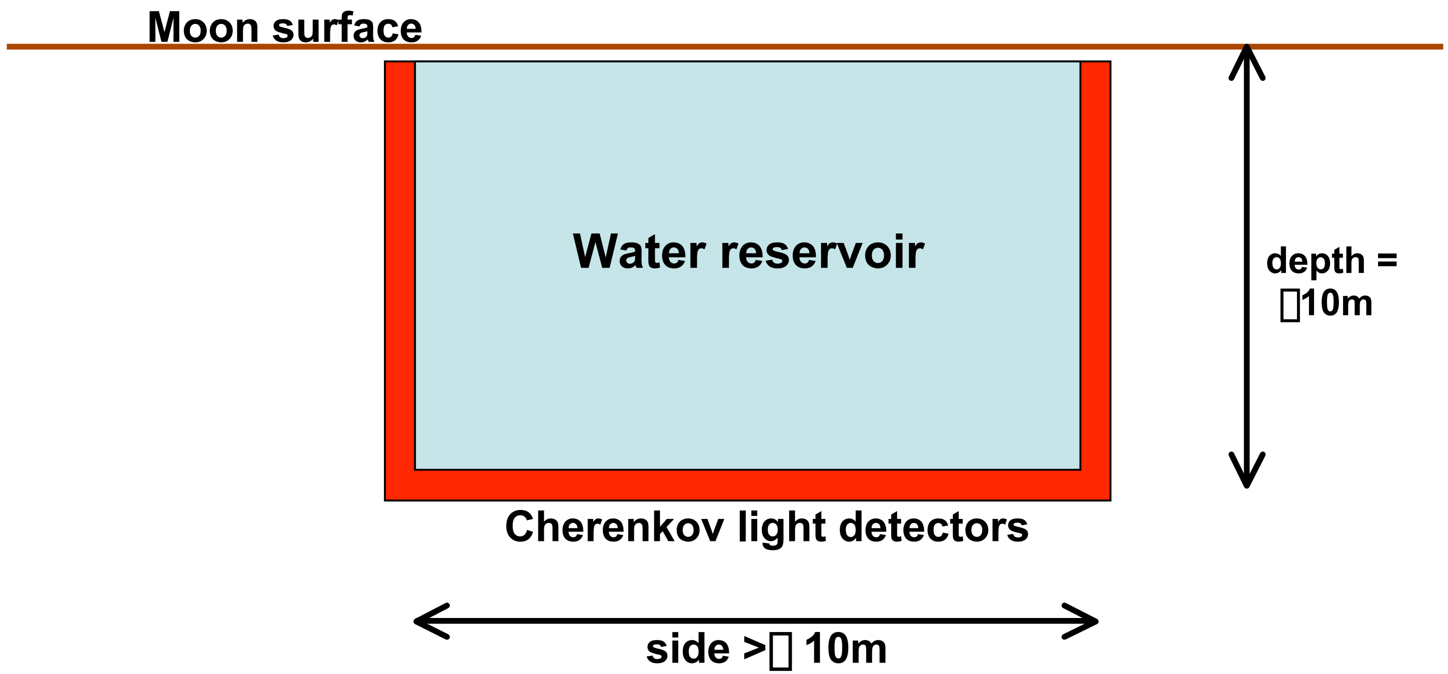
GF $2x2m^2x1sr$
Mass 5t





Rates/(sr*100m2*year)
log (Rate/(sr*100m2*year))
10
9
8
7
6
5
4
3
2
1
0
-1
-2
1
10
100
1000
10000
Energy (TeV)
all
proton
all
proton
all
proton
all
all
proton

Lunar facility for HE gamma rays and HE Cosmic Rays (surface > □100m^2 modules)



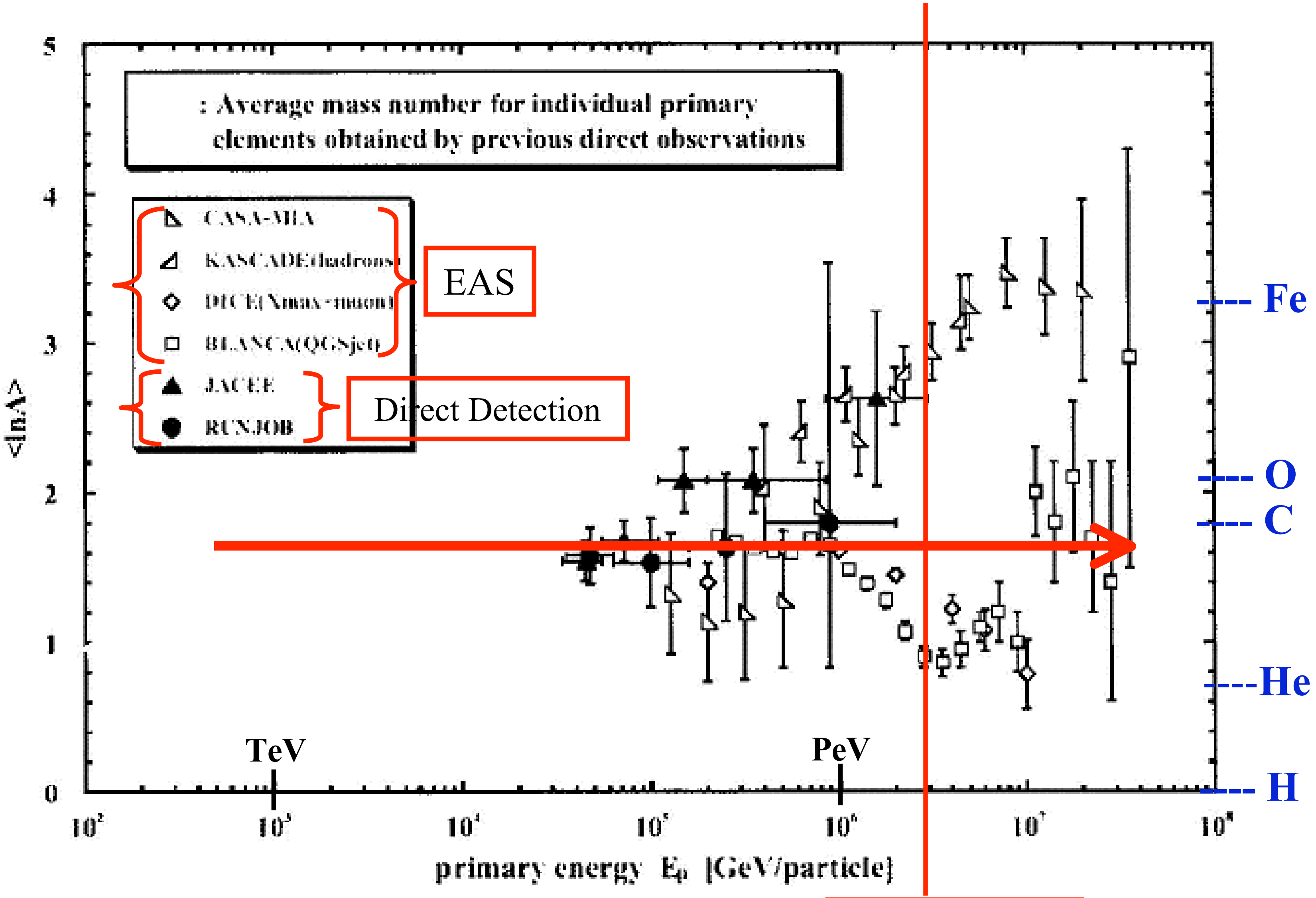
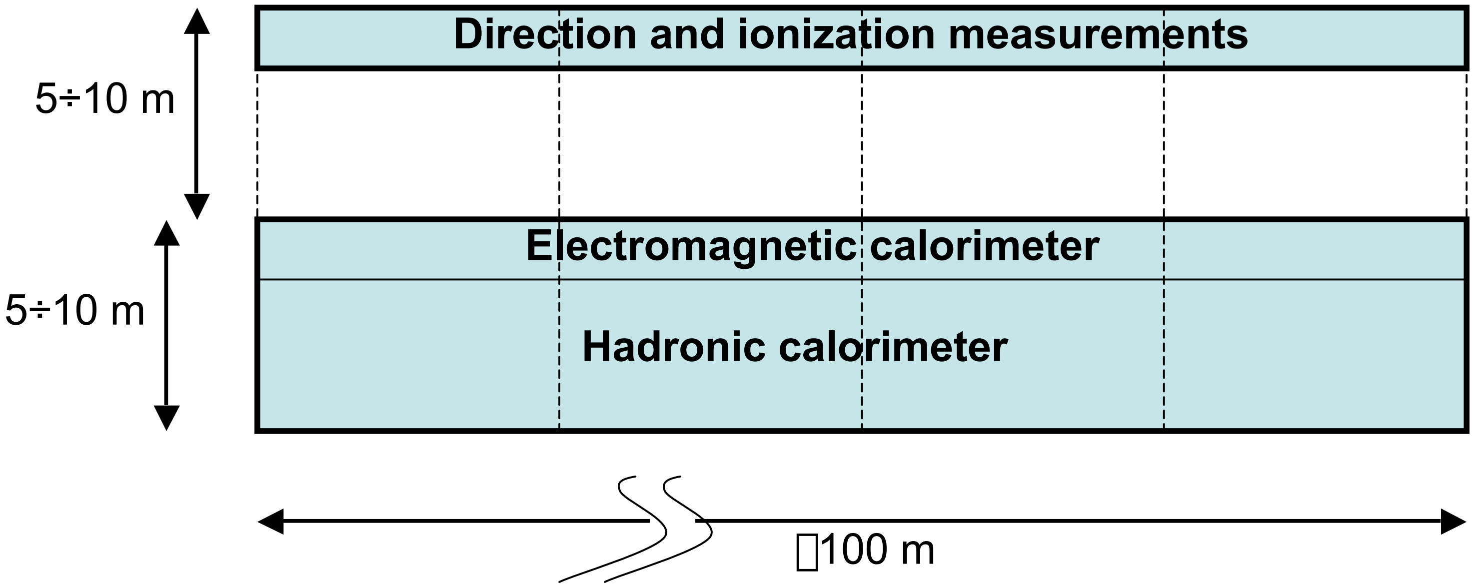
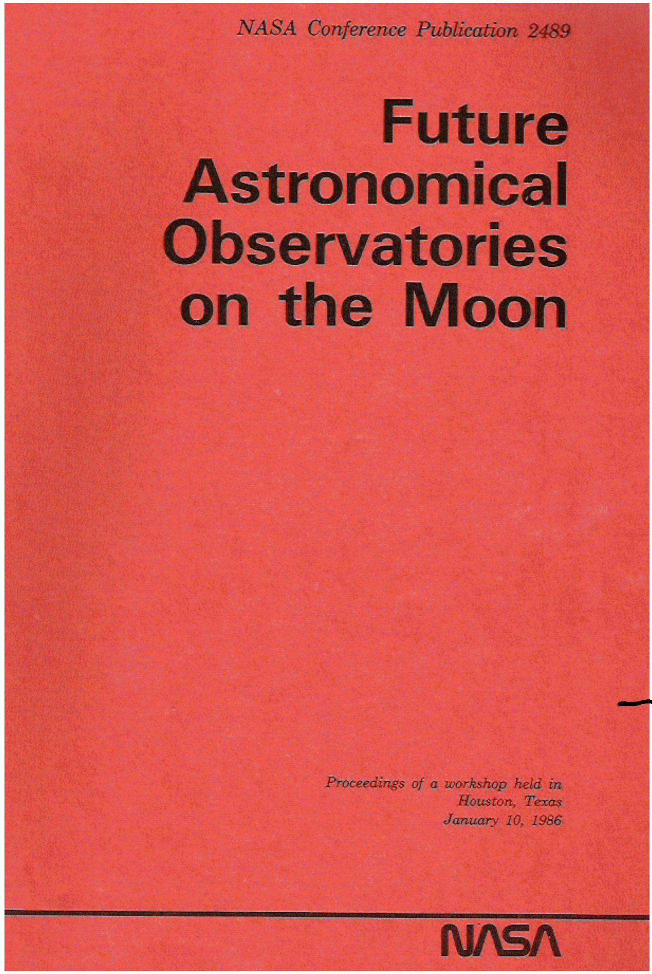


Fig. 3. Energy dependence of average mass number of primary cosmic-ray particles.

Lunar facility for HE gamma rays and HE Cosmic Rays (several □$100 m^2$ modules)





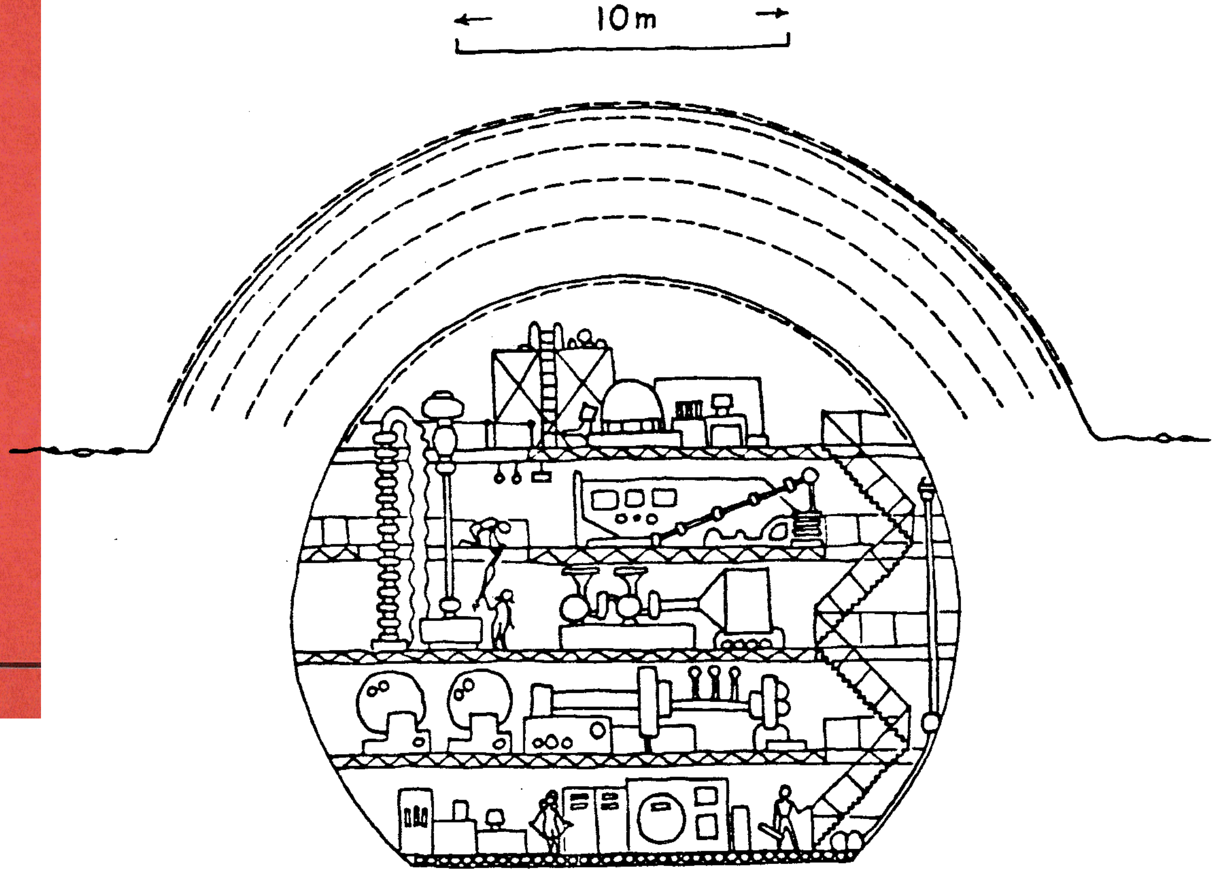
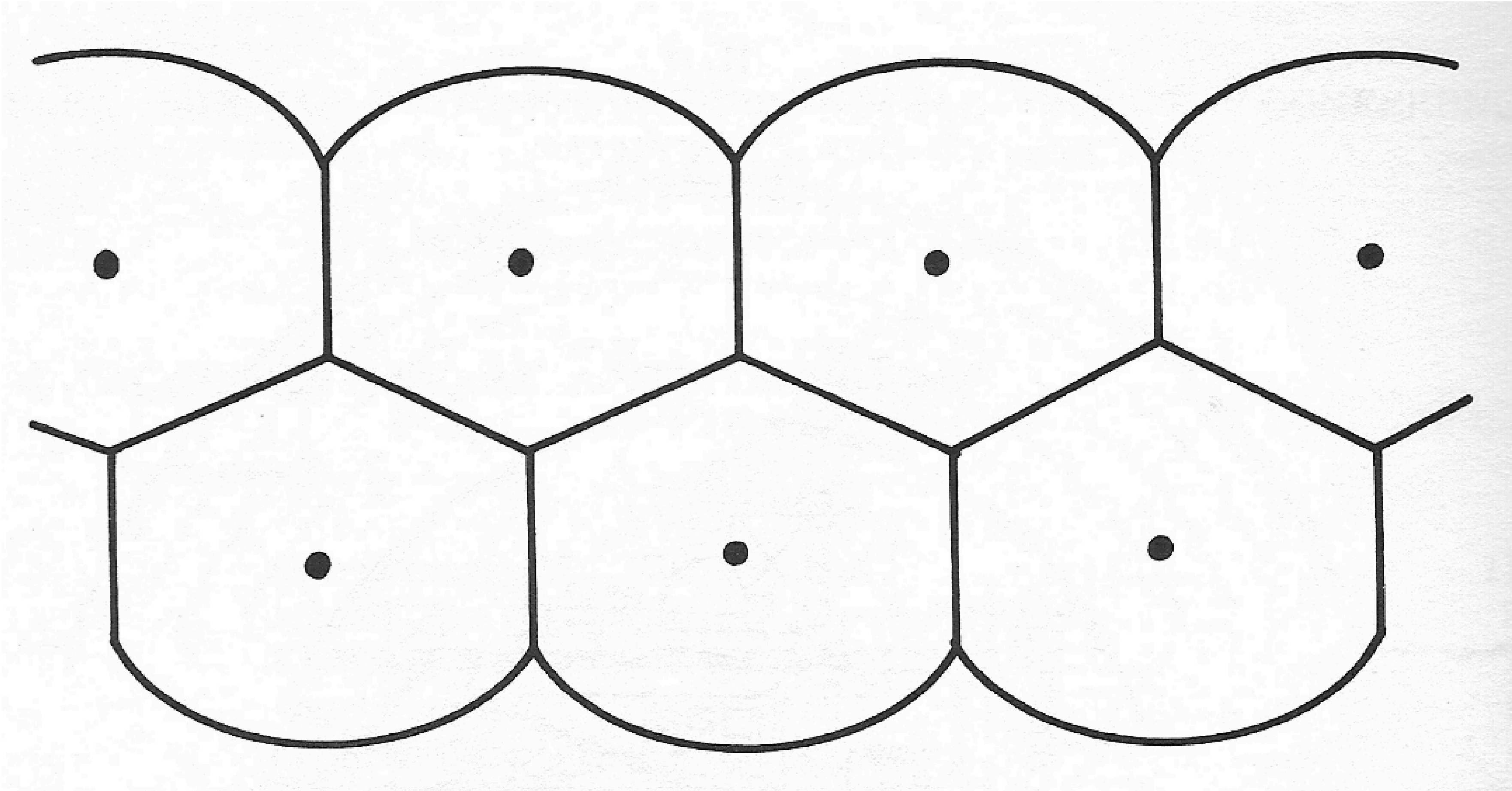
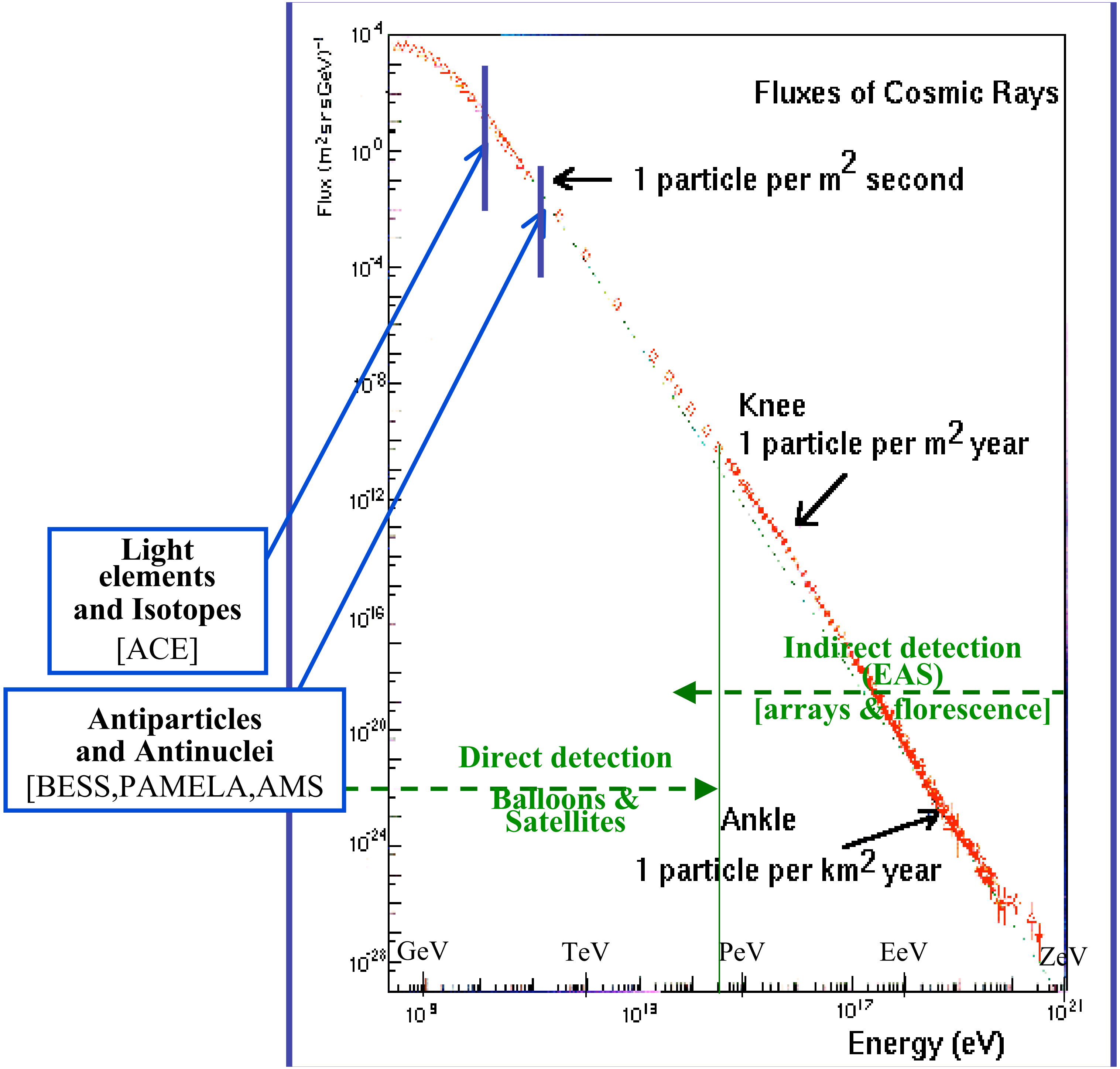
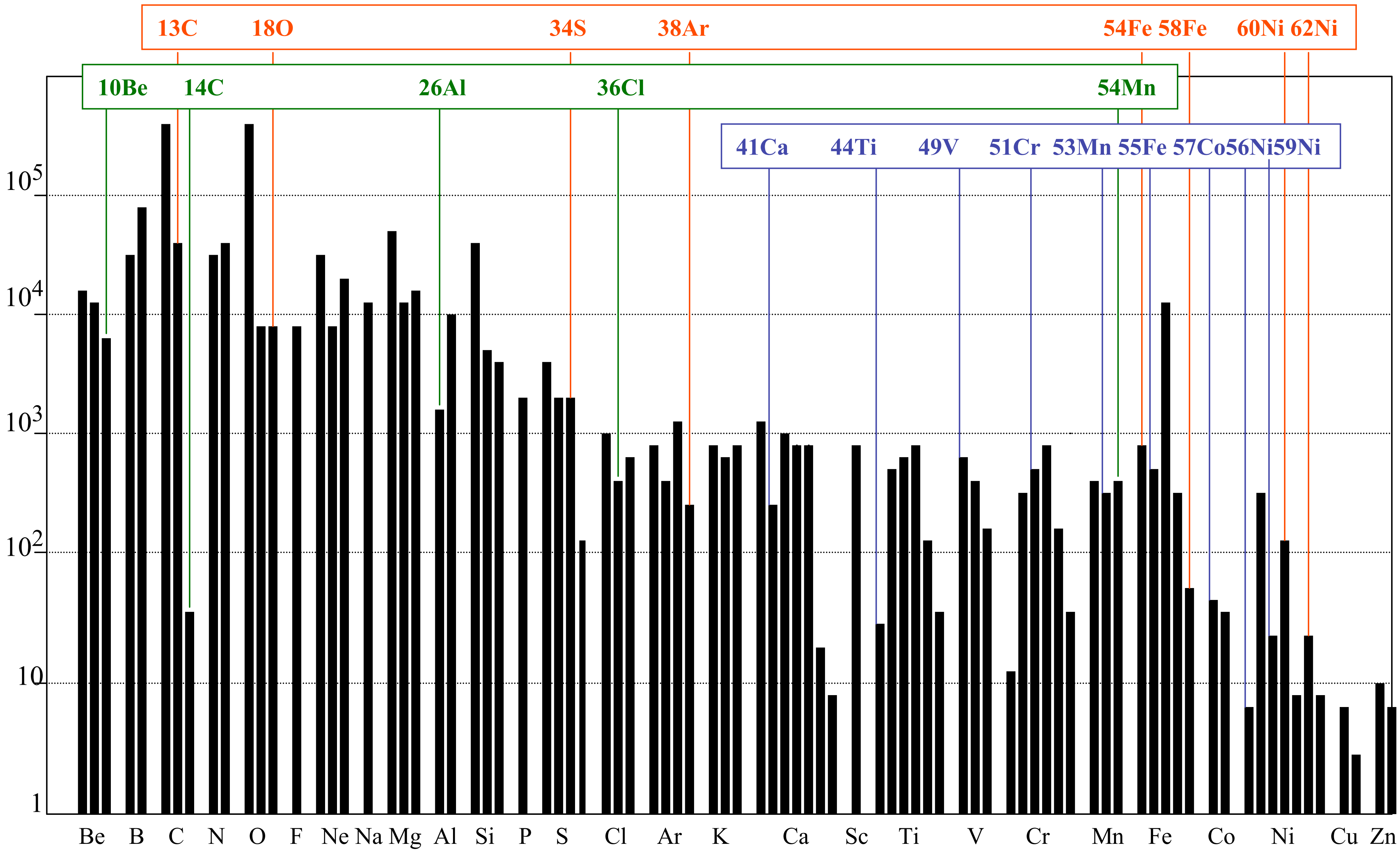


Figure 1.- A large ionization calorimeter built into the shielding of a manufacturing facility or a laboratory on the Moon. The dashed lines represent layers of gas-filled ionization counters.





Fluxes of Cosmic Rays
1 particle per m2 second
Knee
1 particle per m2 year
Indirect detection
(EAS)
[arrays & florescence]
Direct detection
Balloons &
Satellites
Ankle
1 particle per km2 year
GeV
TeV
PeV
EeV
ZeV
Energy (eV)
Light
elements
and Isotopes
[ACE]
Antiparticles
and Antinuclei
[BESS,PAMELA,AMS

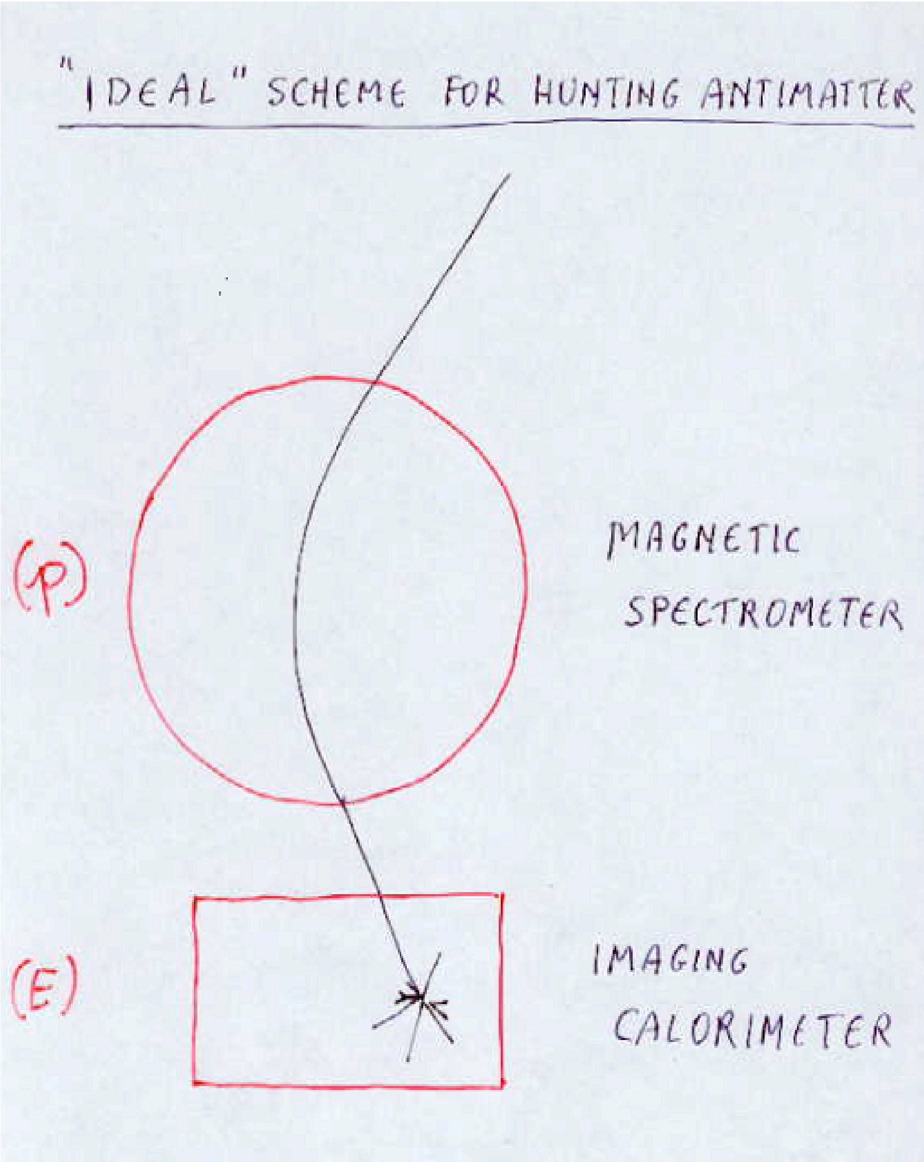


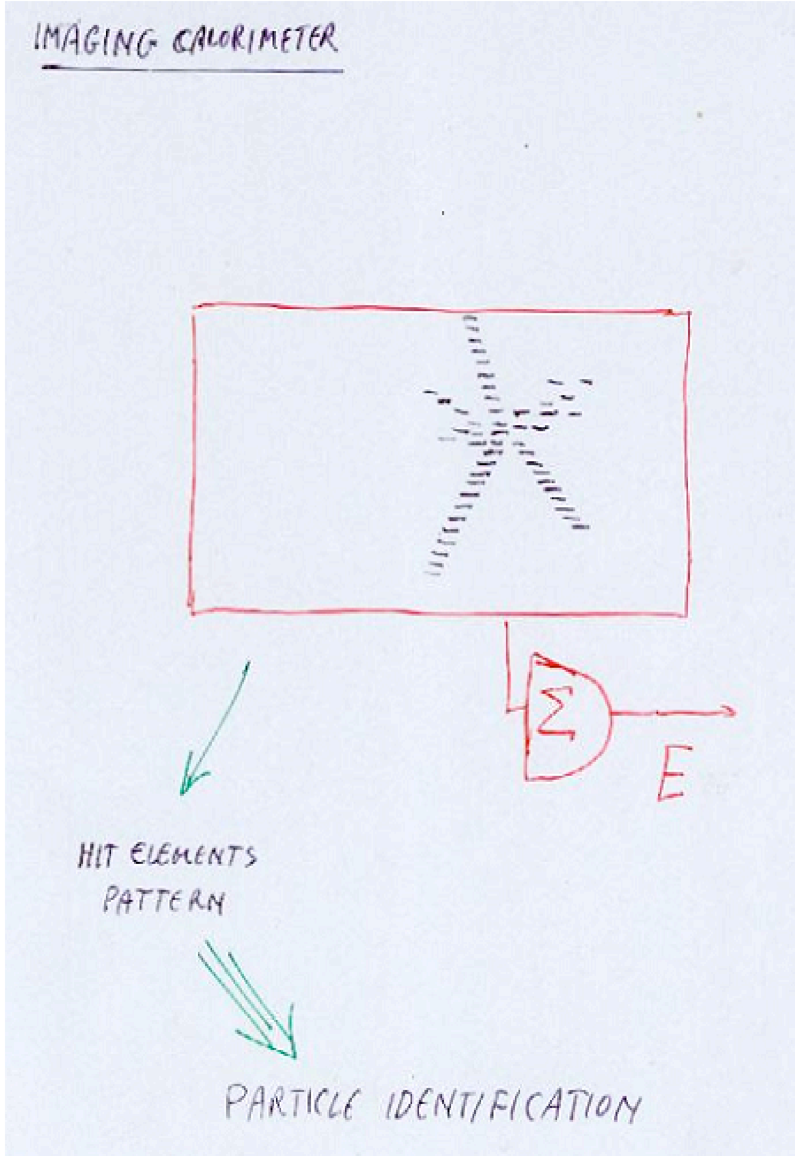
LISA project for ASTROMAG: Events/3years (80% duty cycl., losses 50%)

“rare” isotopes:
nucleosintetic origin of CR

Beta decay:
Residence time in the Galaxy

electronic capture:
time between nucleos. and accel.


"IDEAL" SCHEME FOR HUNTING ANTIMATTER
(P)
MAGNETIC
SPECTROMETER
(E)
IMAGING
CALORIMETER

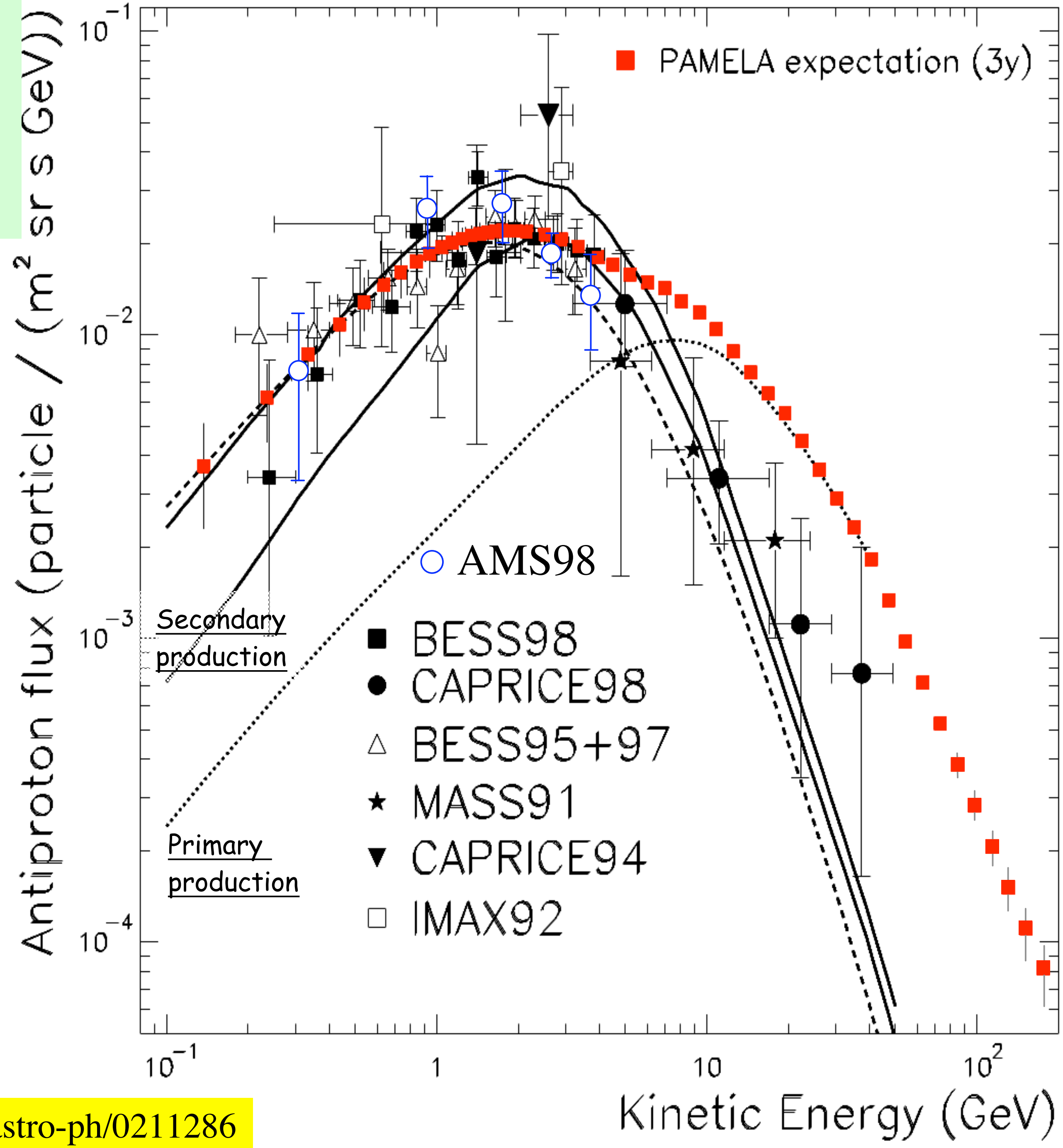

IMAGING CALORIMETER
Σ
E
HIT ELEMENTS
PATTERN
PARTICLE IDENTIFICATION

PAMELA ANTIPROTONS expectation

Secondary production (upper and lower limits) Simon et al.

Primary production from □ □ annihilation

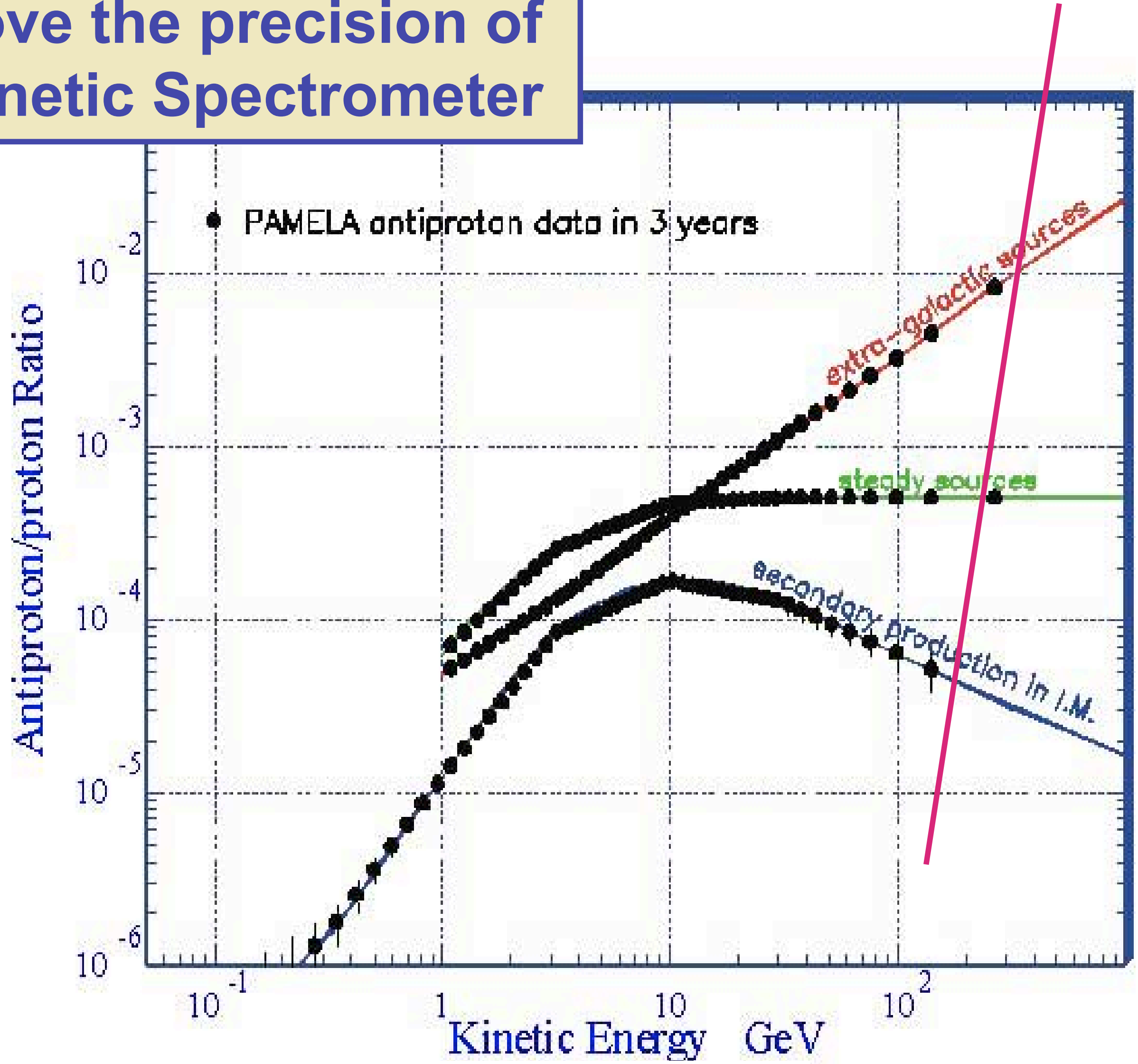
(m(□) = 964 GeV)



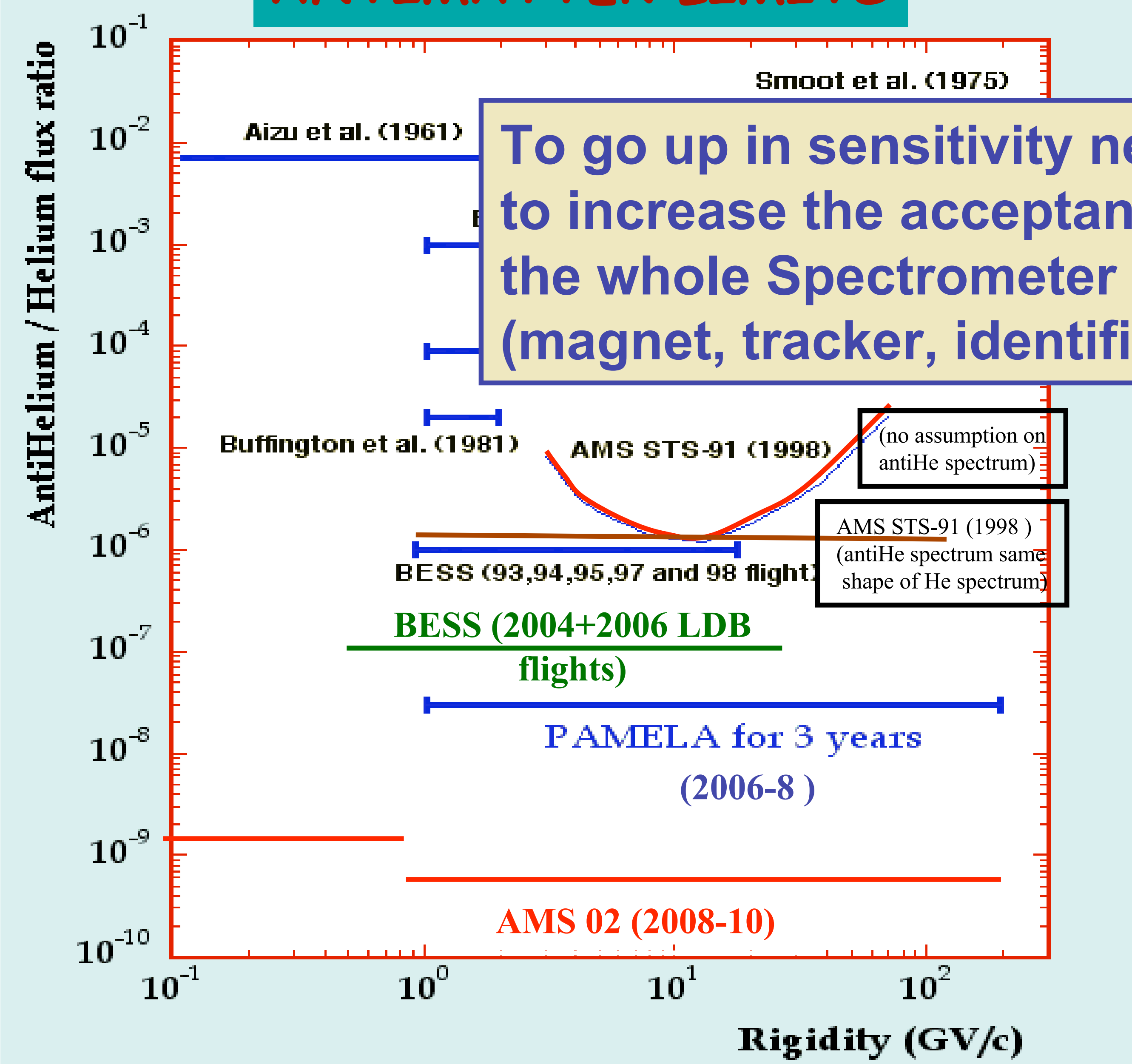
P. Picozza and A. Morselli, astro-ph/0211286

To go up in Energy needed to improve the precision of the Magnetic Spectrometer

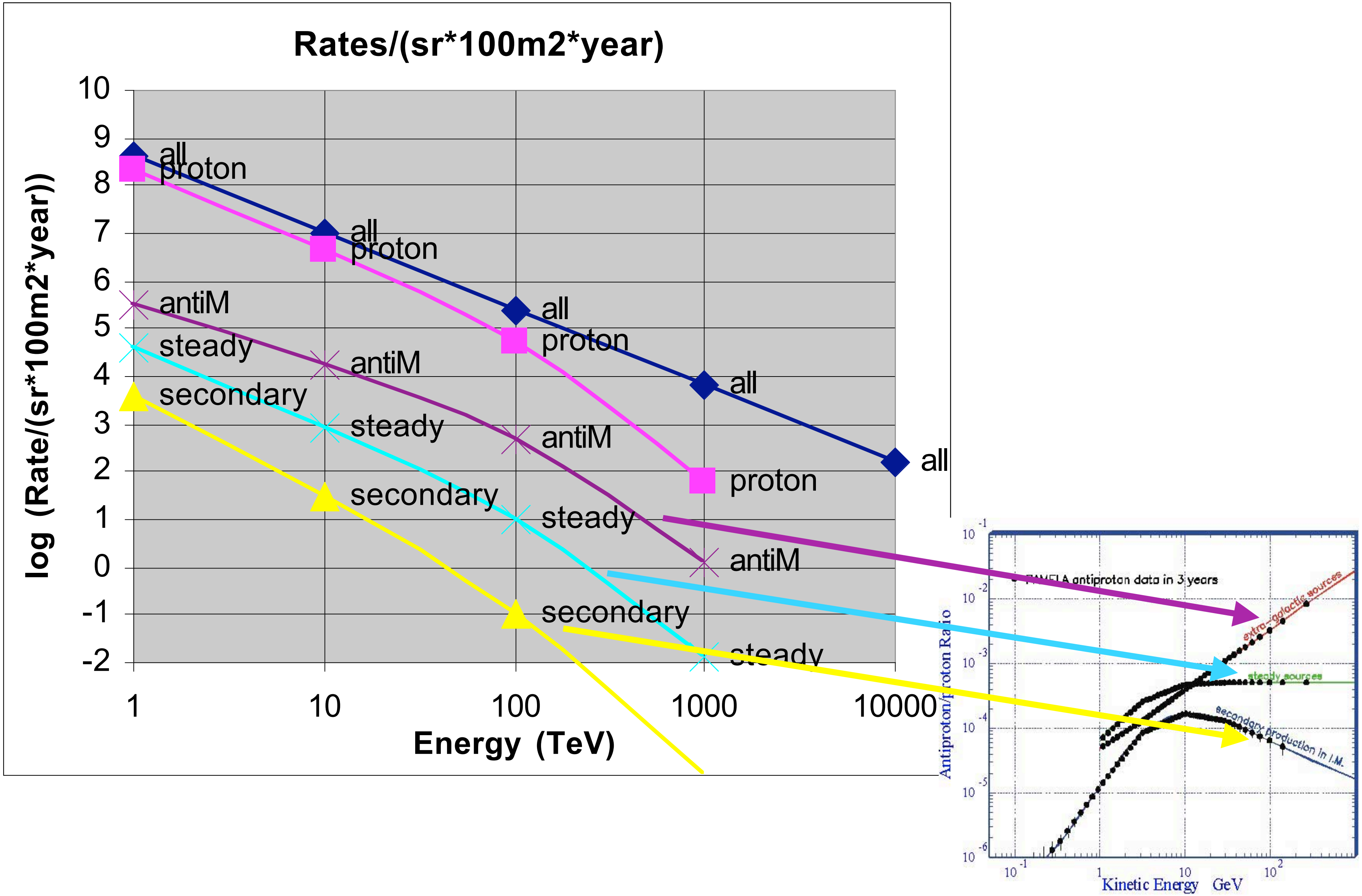
Spillover of p on antip = 0.2 of the antip flux

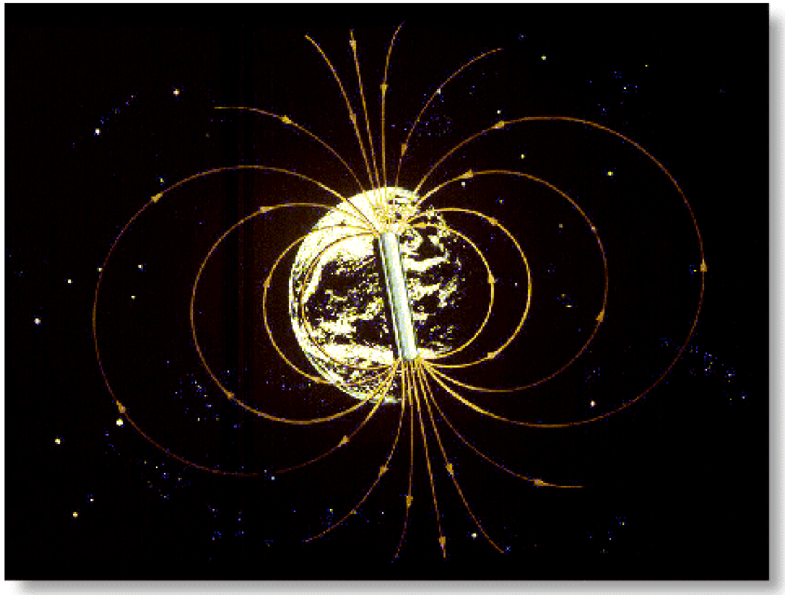


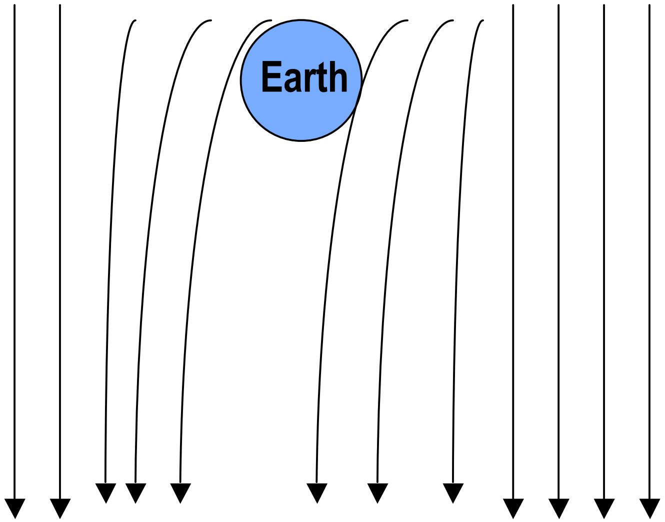
ANTIMATTER LIMITS

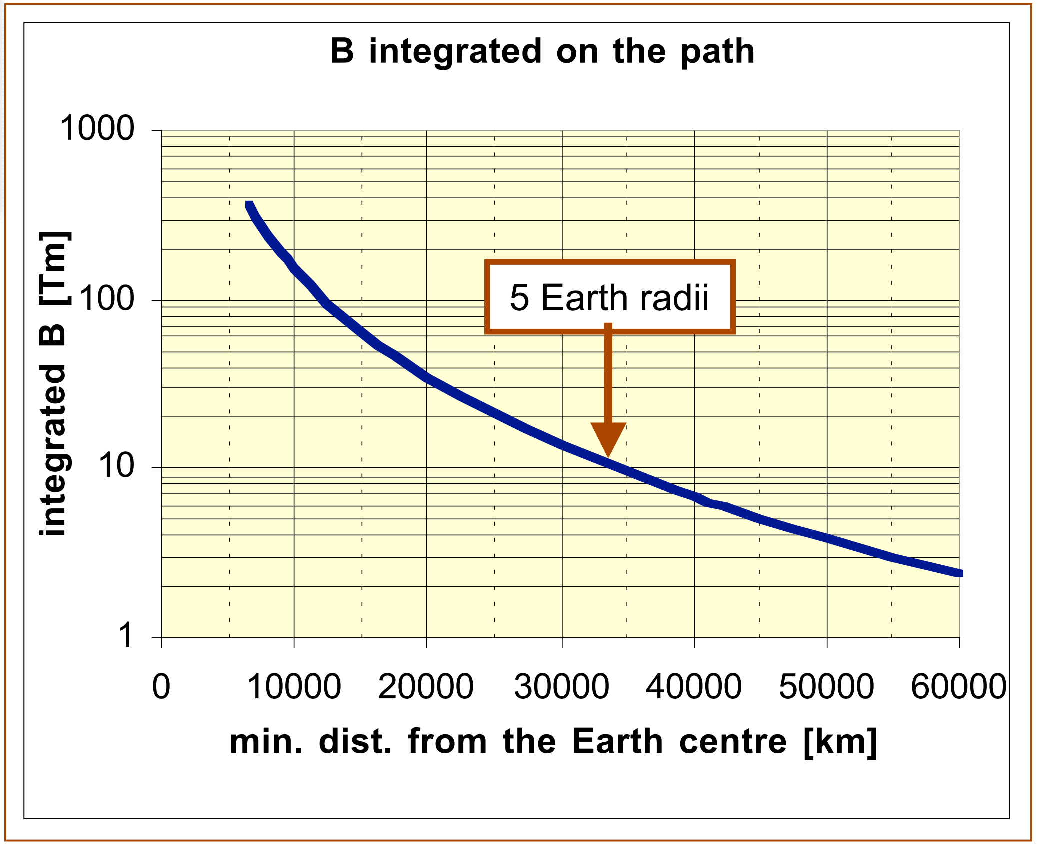


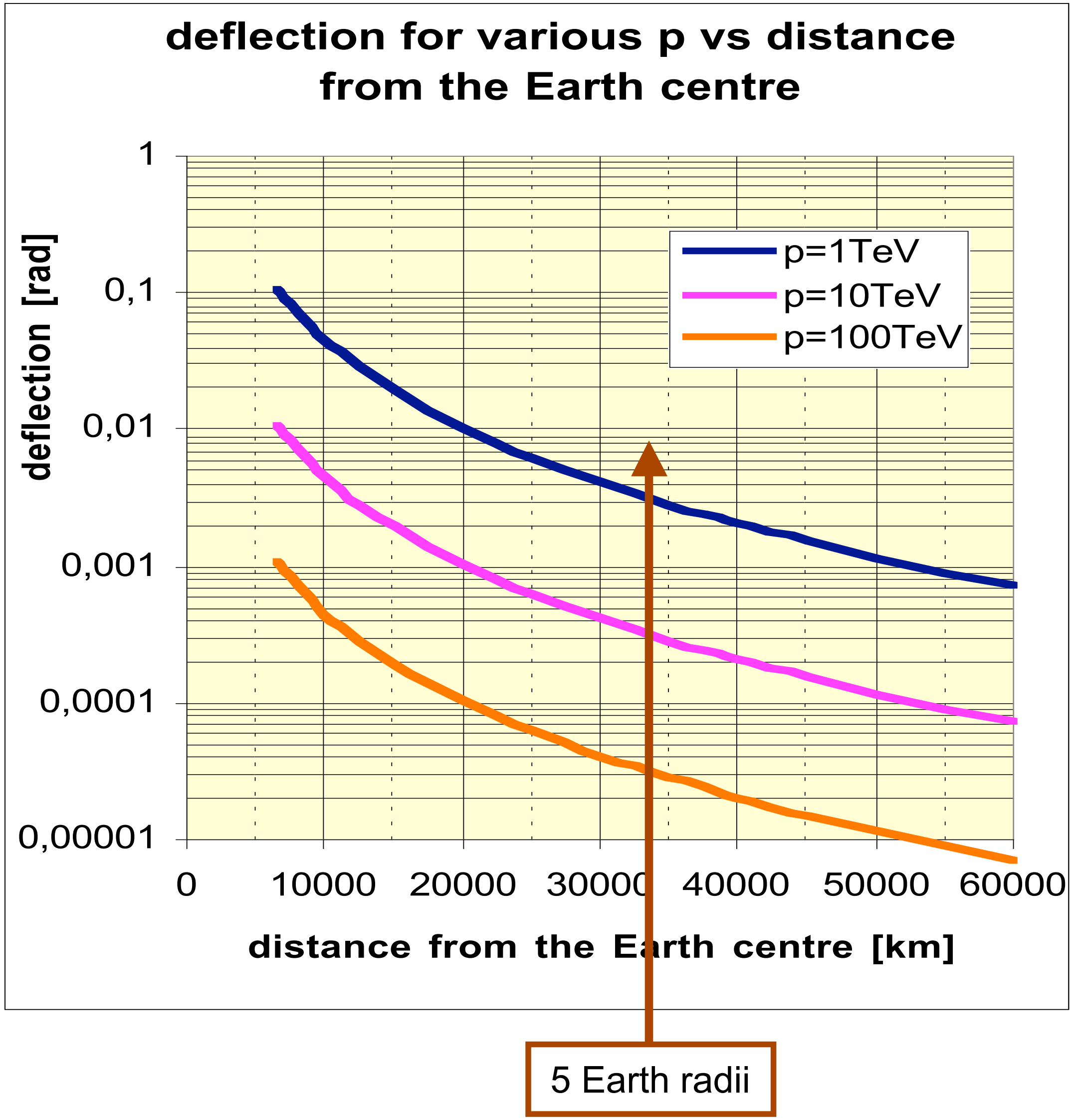
To go up in sensitivity needed to increase the acceptance of the whole Spectrometer (magnet, tracker, identification)

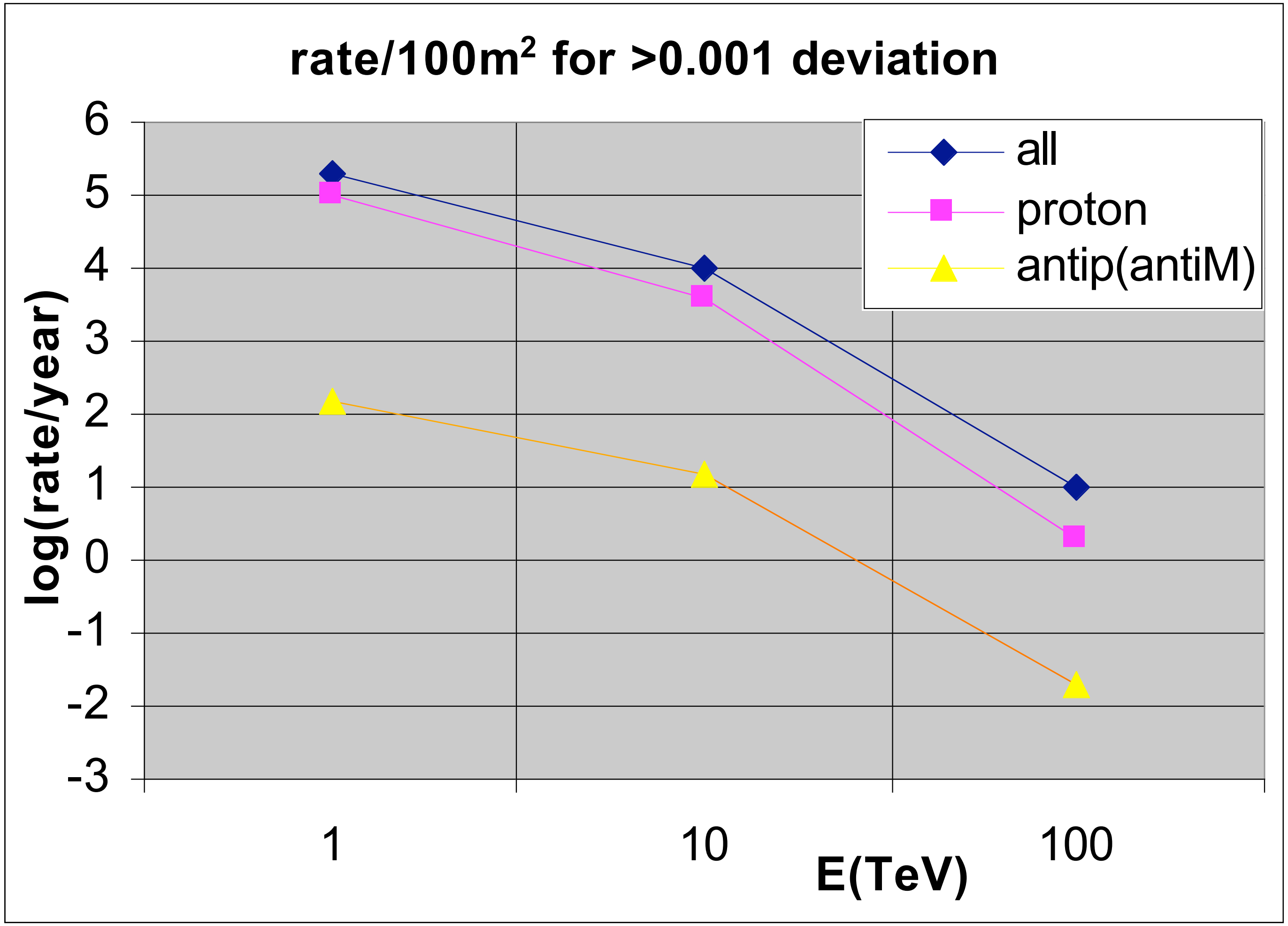

Rates/(sr*100m2*year)
log (Rate/(sr*100m2*year))
Energy (TeV)
10
9
8
7
6
5
4
3
2
1
0
-1
-2
1
10
100
1000
10000
all
proton
antiM
steady
secondary
extra-galactic sources
steady sources
secondary production in I.M.
Antiproton/Proton Ratio
Kinetic Energy GeV



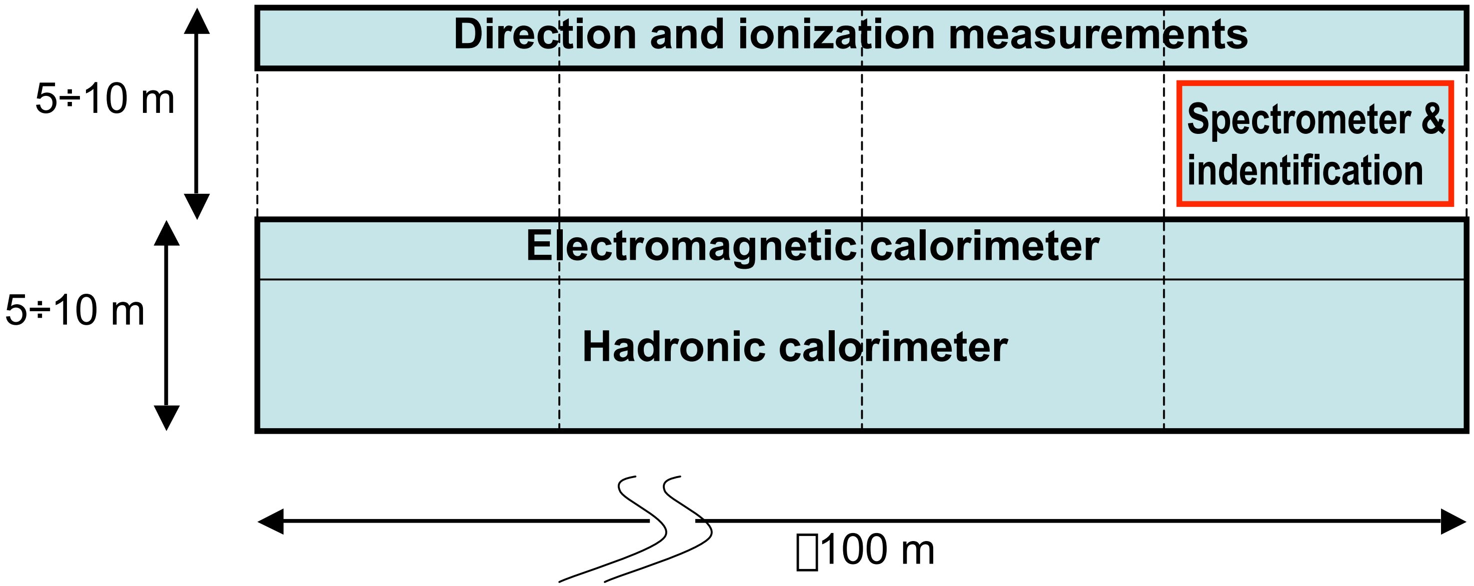

Earth

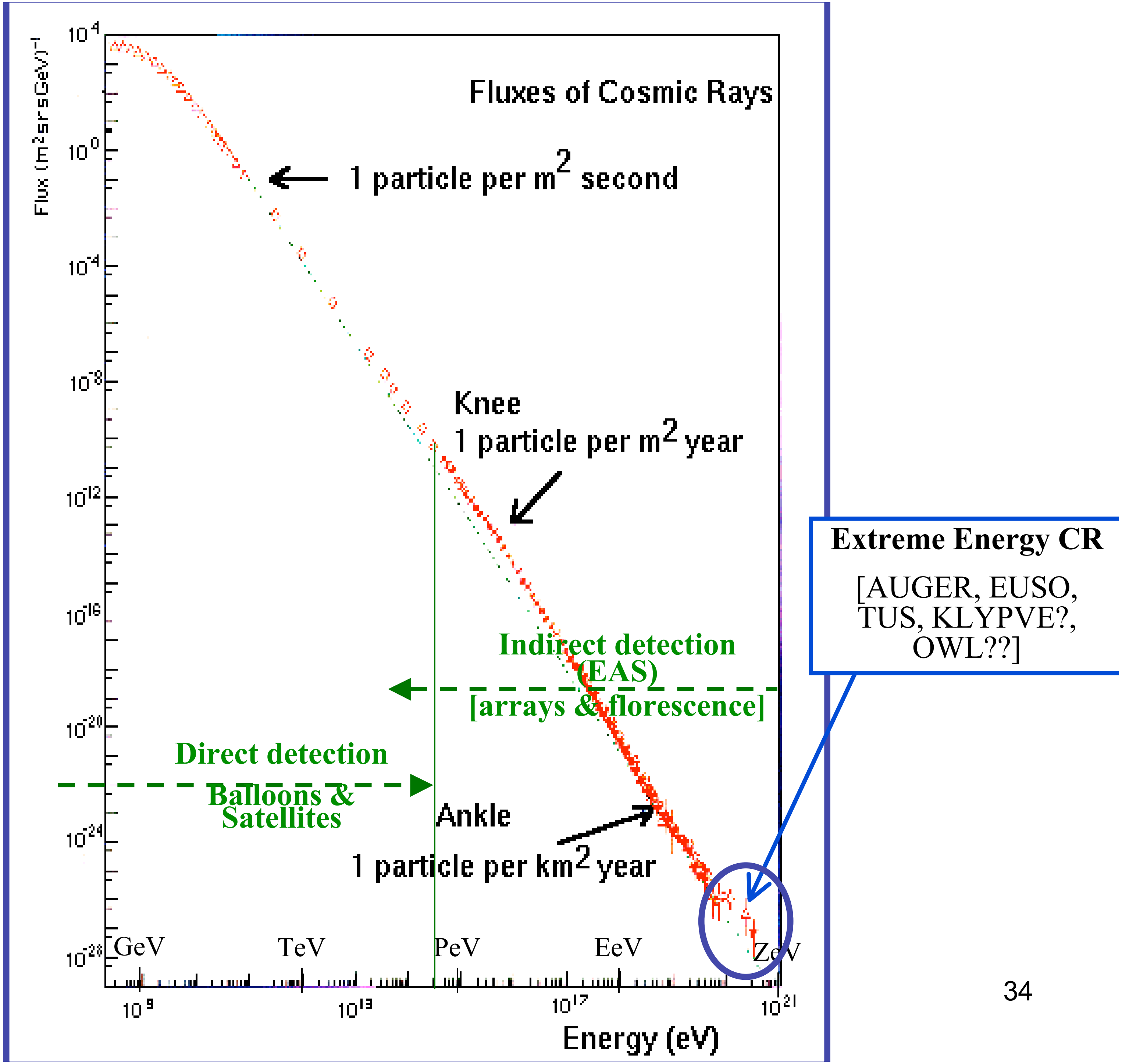

B integrated on the path
1000
100
10
1
integrated B [Tm]
5 Earth radii
0
10000
20000
30000
40000
50000
60000
min. dist. from the Earth centre [km]


deflection for various p vs distance from the Earth centre
deflection [rad]
1
0,1
0,01
0,001
0,0001
0,00001
0
10000
20000
30000
40000
50000
60000
distance from the Earth centre [km]
p=1TeV
p=10TeV
p=100TeV
5 Earth radii


rate/100m2 for >0.001 deviation
log(rate/year)
6
5
4
3
2
1
0
-1
-2
-3
1
10
100
E(TeV)
all
proton
antip(antiM)

Lunar facility for HE gamma rays and HE Cosmic Rays




Fluxes of Cosmic Rays
1 particle per m2 second
Knee
1 particle per m2 year
Indirect detection (EAS)
[arrays & florescence]
Direct detection
Balloons & Satellites
Ankle
1 particle per km2 year
GeV
TeV
PeV
EeV
ZeV
Flux (m2 sr s GeV)-1
Energy (eV)
Extreme Energy CR
[AUGER, EUSO, TUS, KLYPVE?, OWL??]

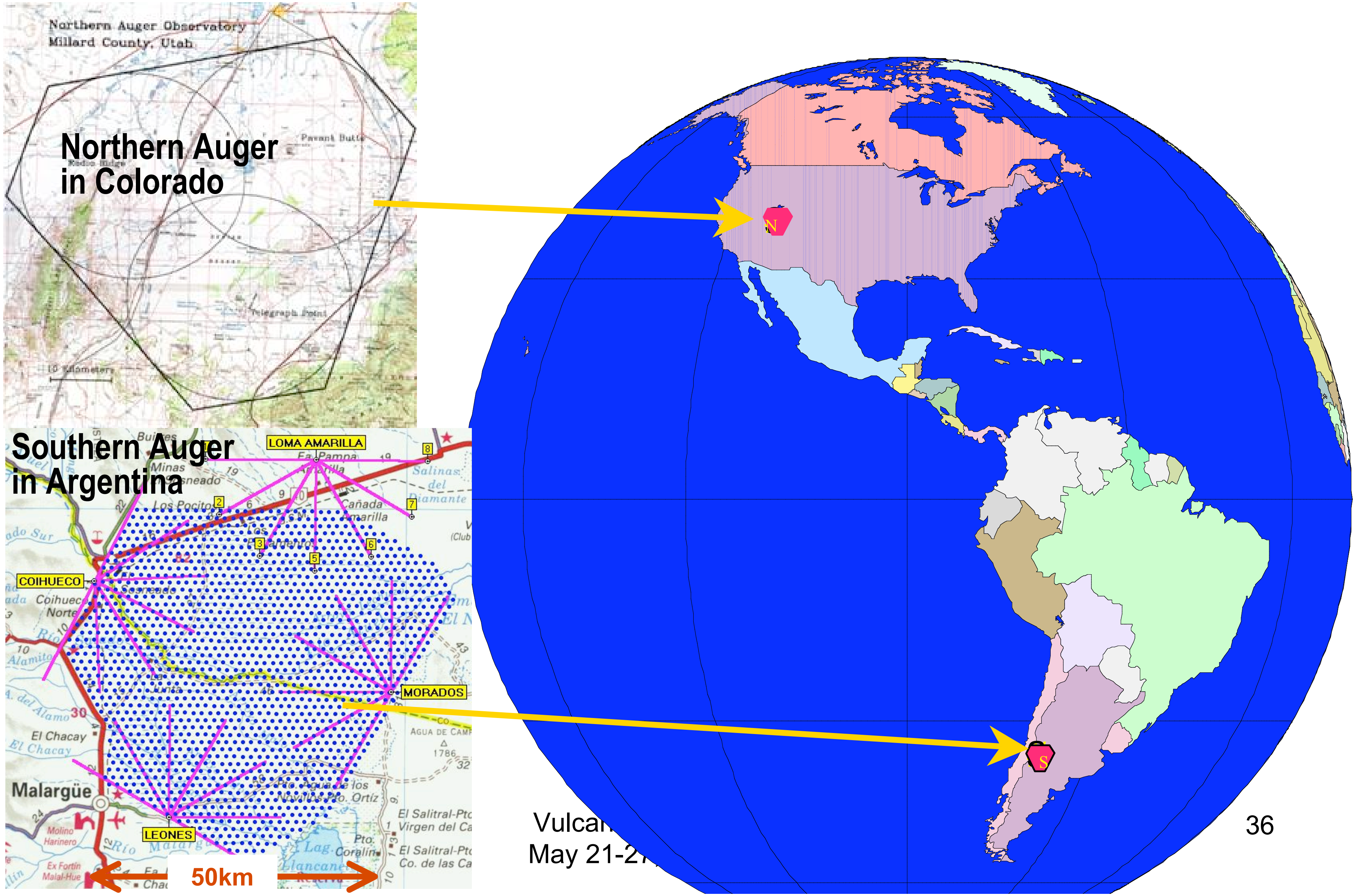
Ultra High Energy cosmic rays

Extragalactic (gyro-radius)

Unknown acceleration mechanism:
- no sources identified in 50-100 Mpc distance

Possible UP-DOWN generation:
- e.g. topological defect decay

Pierre-Auger Observatory



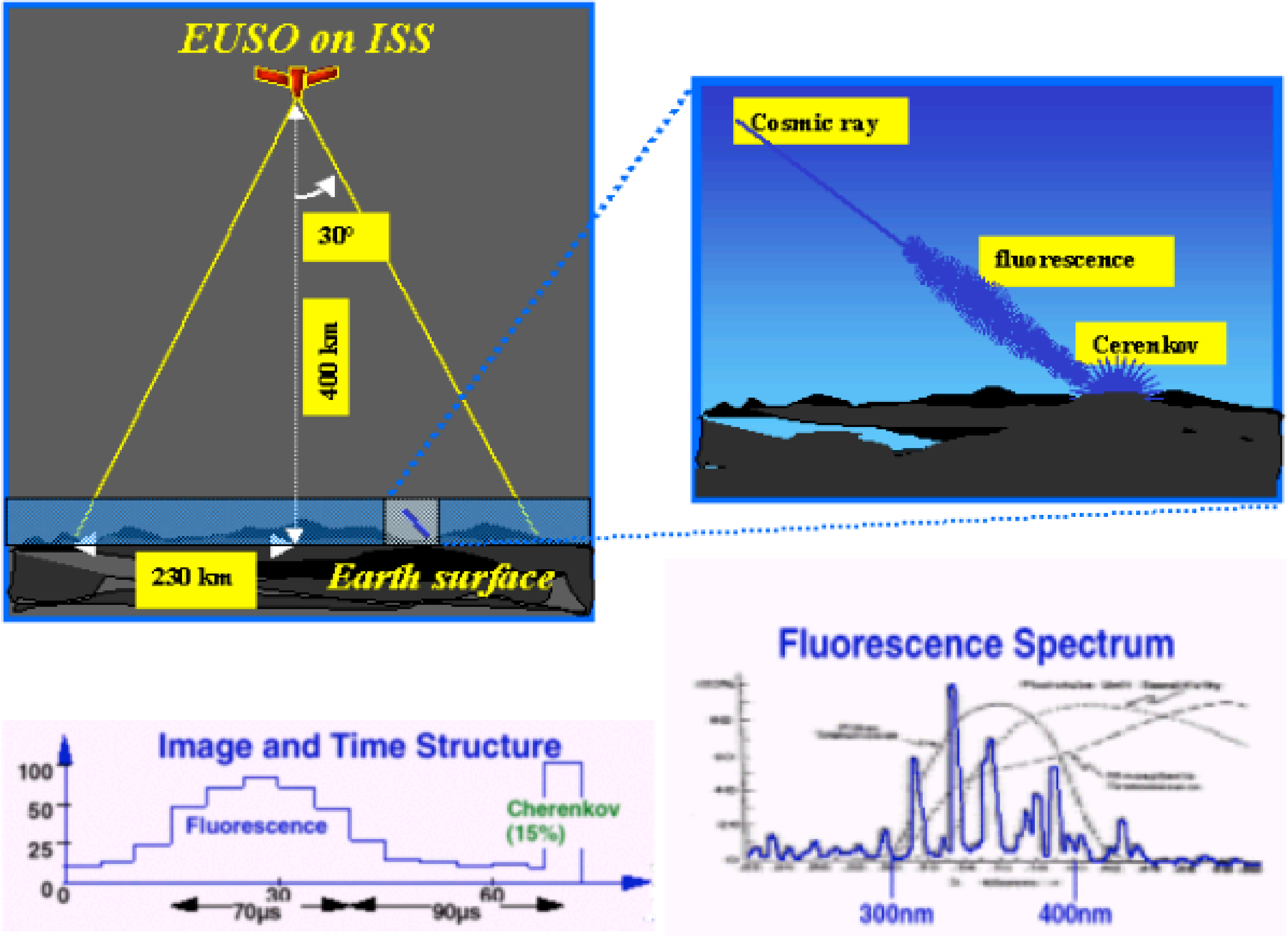
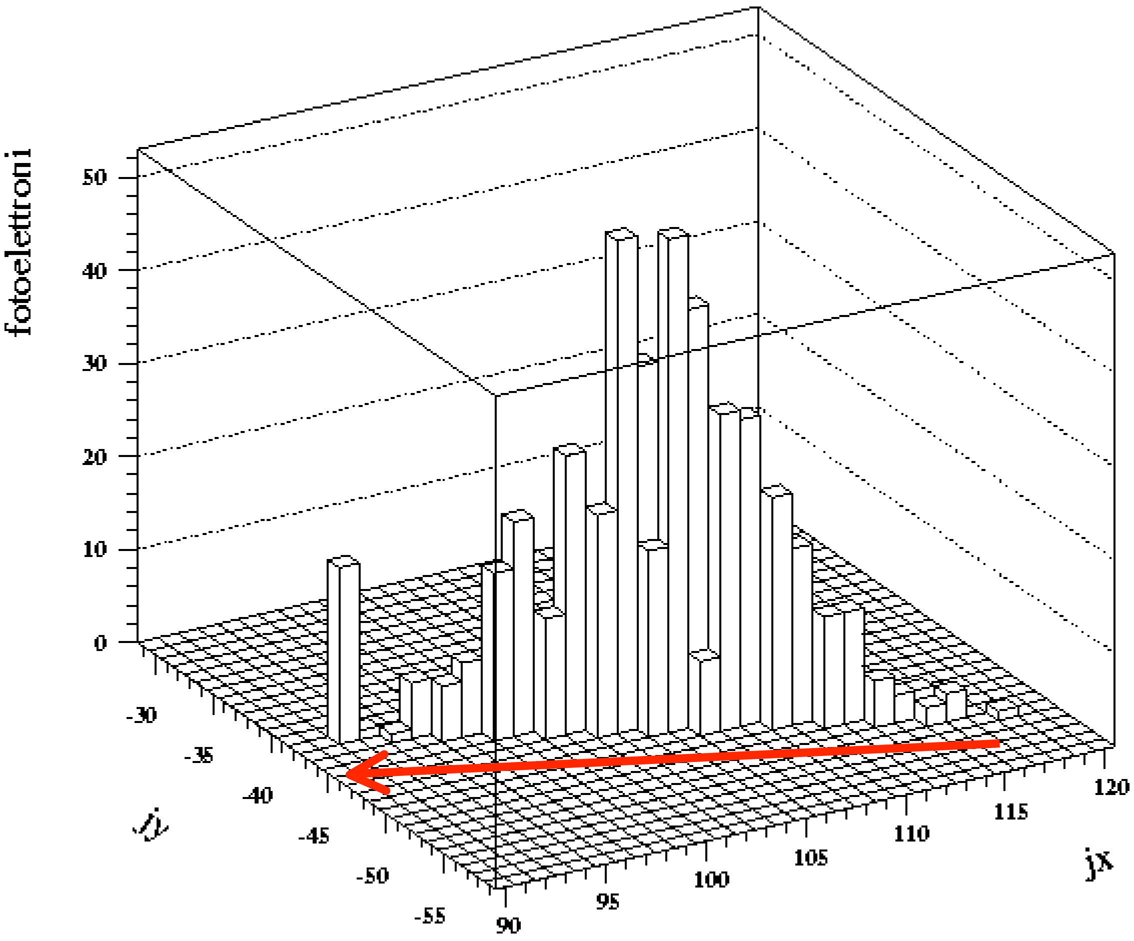
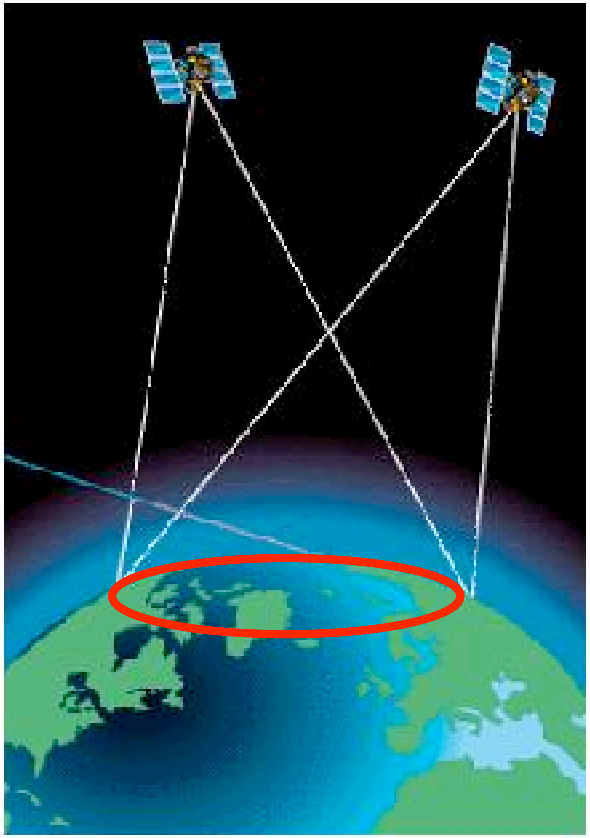


Fig. 2.1 – Artist view of the ***EUSO*** concept. The shower development occurs in the atmosphere layers below 30-40 km a.s.l.; the isotopic fluorescence emission is proportional at any depth to the number of charged particles (mainly electrons) present in the shower front: $N_e \approx E_{eV} / (1.4 \times 10^9)$. The UV yield is ≈4 photons per meter of electron track, almost independent from air pressure and temperature.


fotoelettroni
50
40
30
20
10
0
-30
-35
-40
-45
-50
-55
jy
90
95
100
105
110
115
120
jx

The OWL Concept



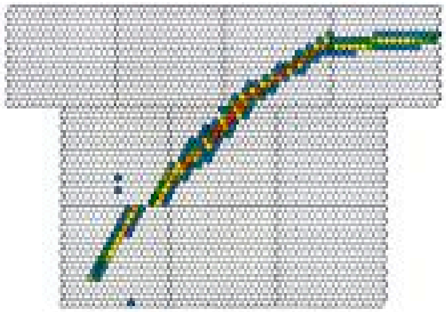
Use air fluorescence technique to image 300 → 400 nm photons in ~ 0.1° pixels (with 10 ns → μs timing), from low Earth, equitorial orbit, airshowers induced by E $\gtrsim 10^{19}$ eV cosmic rays

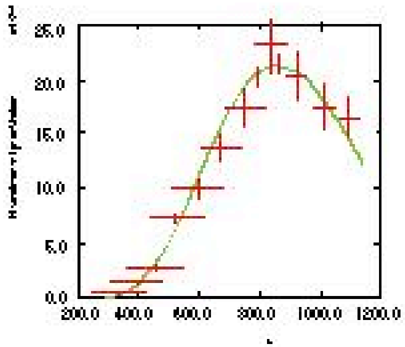
Wide angle (~ 60° full, FOV) optics at a 640 km orbit in a stereo configuration → an asymptotic, *instantaneous* aperture ~ 3 x 10^6 km^2-ster

10% duty cycle → *effective* aperture ~ 3 x 10^5 km^2-ster

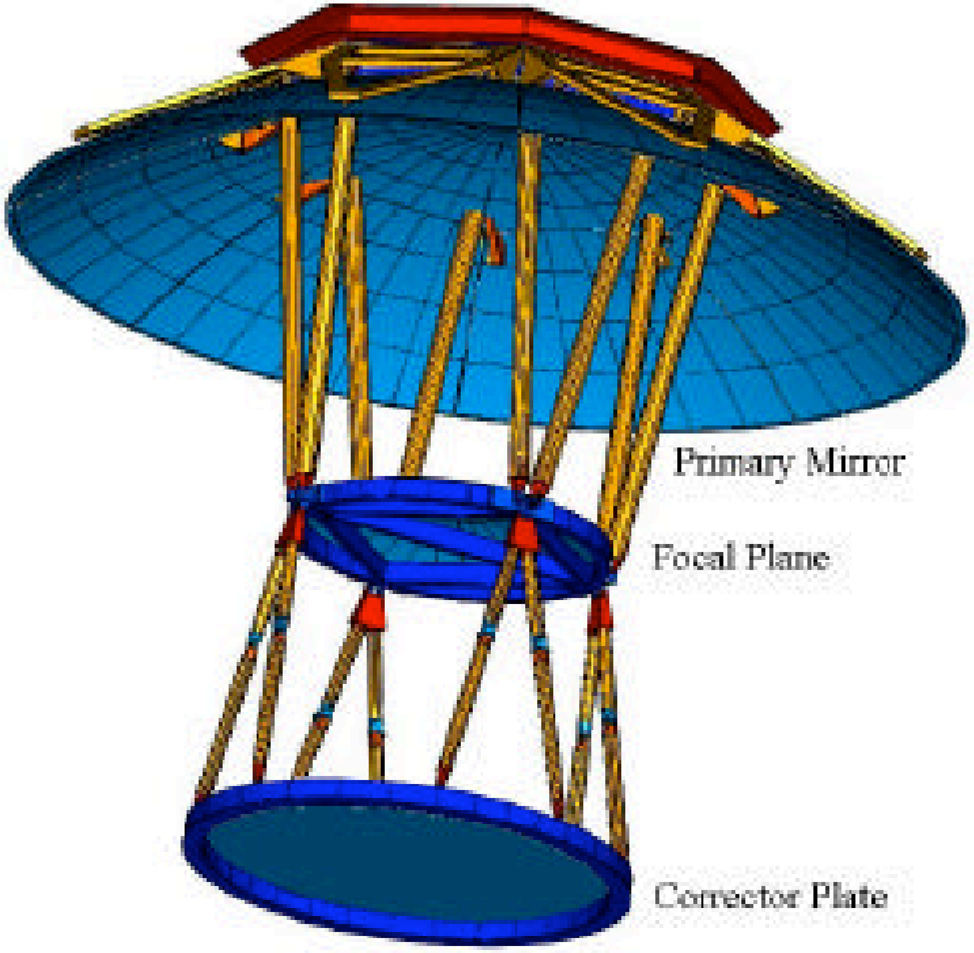
Assuming Φ_{CR} (E) ~ $E^{-2.75}$, the asymptotic OWL stereo aperture leads to ~ 3000 events/year with E $\gtrsim 10^{20}$ eV

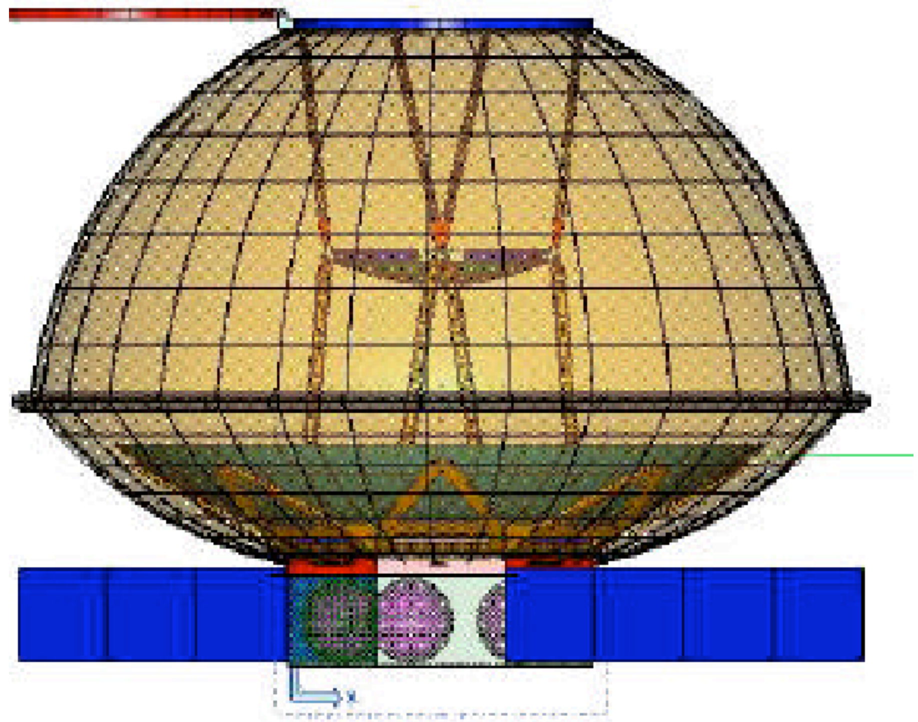
OWL could be a stepping stone to viewing majority of night side atmosphere



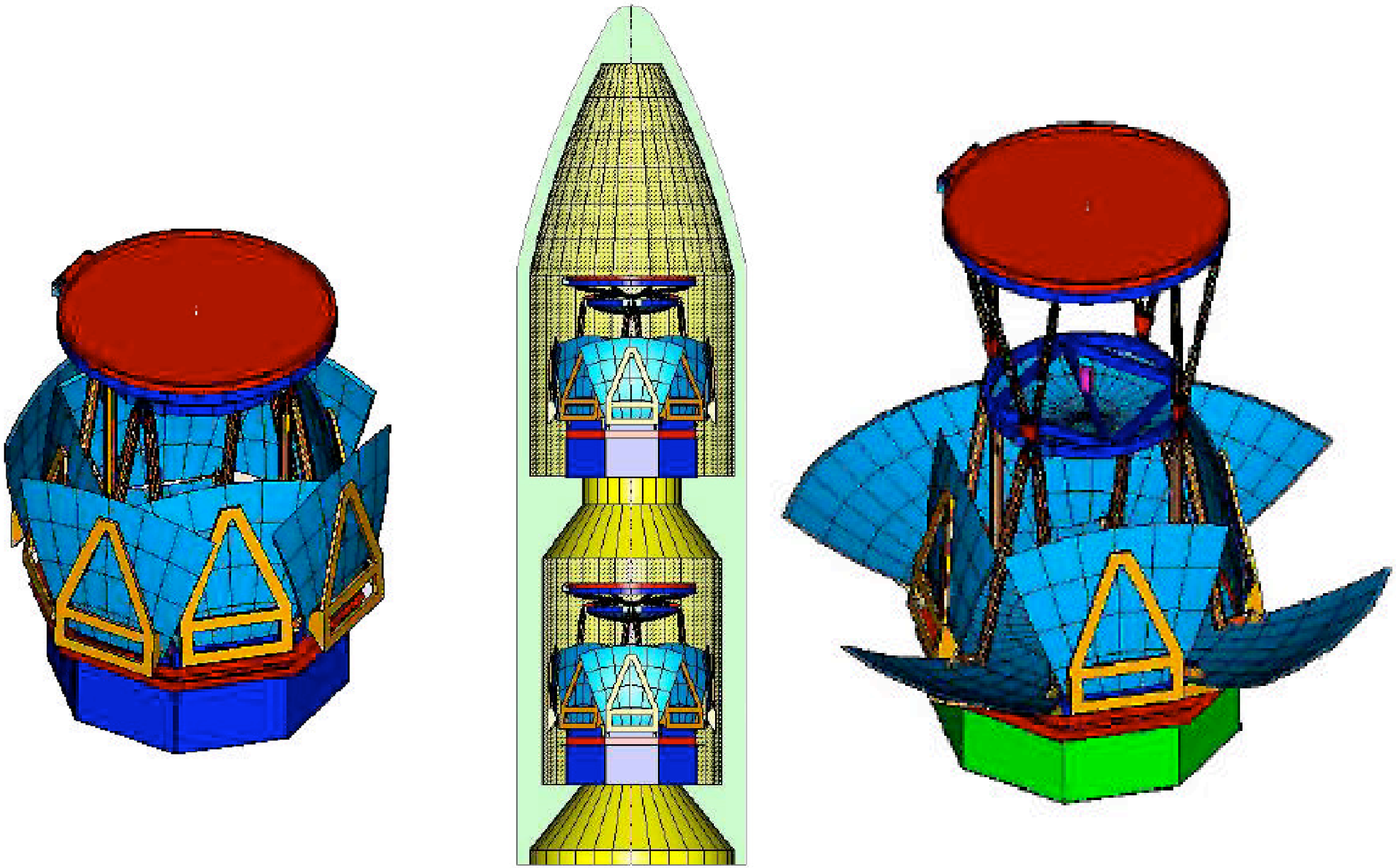


A proposal from NASA: OWL





Deployment of OWL from a Delta 4050-H-19

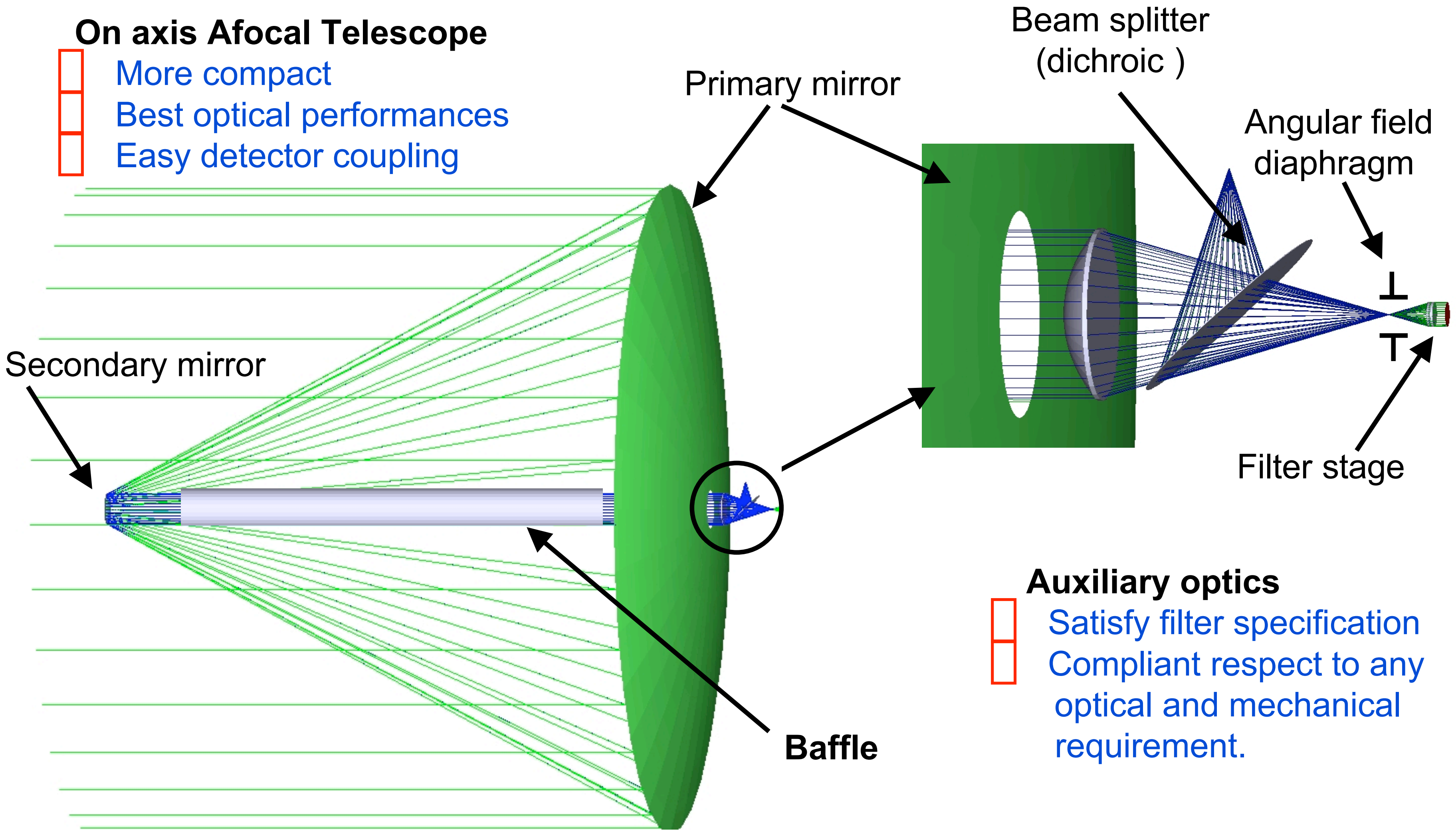


Moon Base: candidate optical configurations

INOA

On axis Afocal Telescope

- More compact
- Best optical performances
- Easy detector coupling



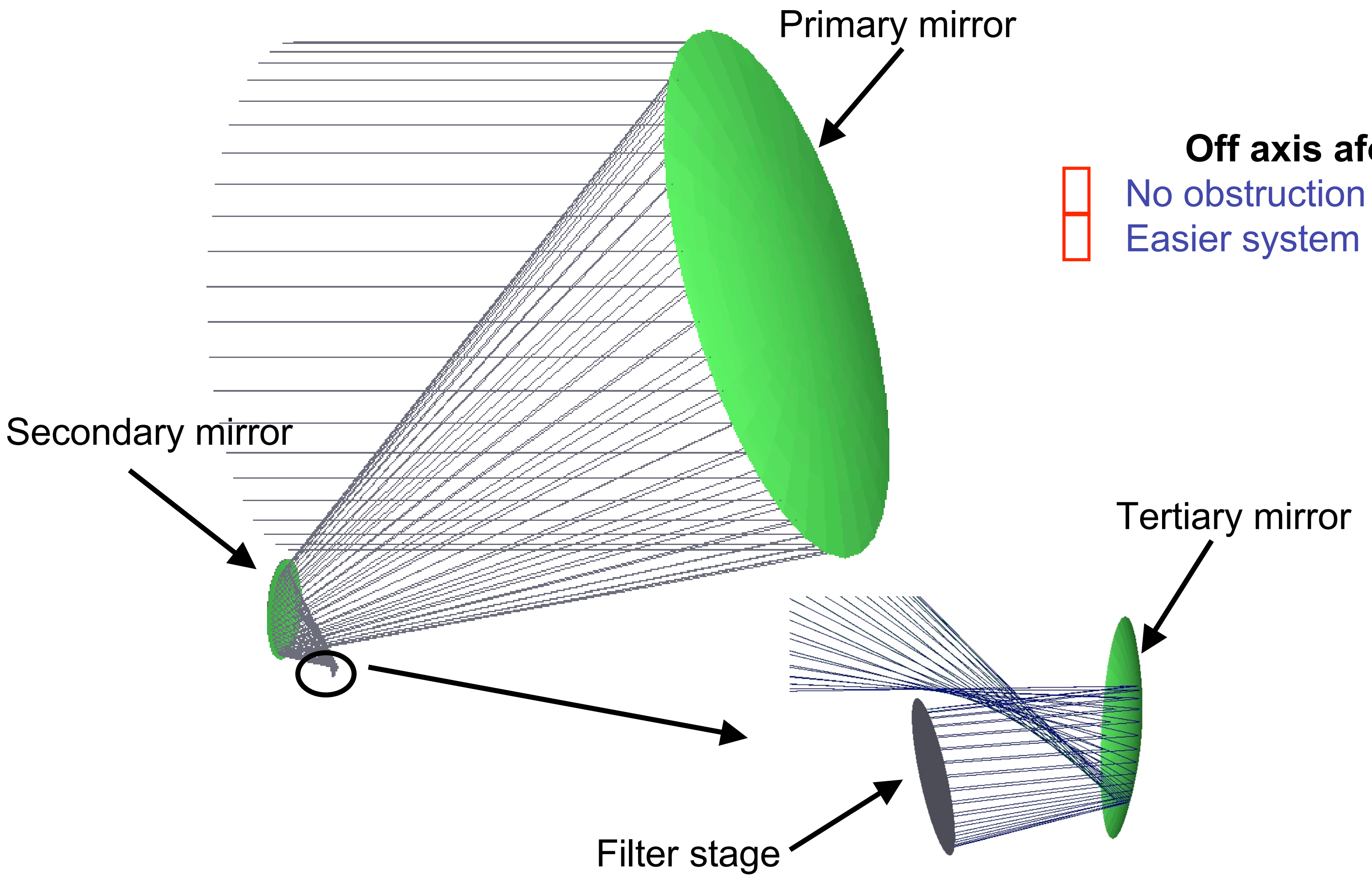
Auxiliary optics

- Satisfy filter specification
- Compliant respect to any optical and mechanical requirement.

Mechanical tolerances **Can be solved with active control of mirror surface**

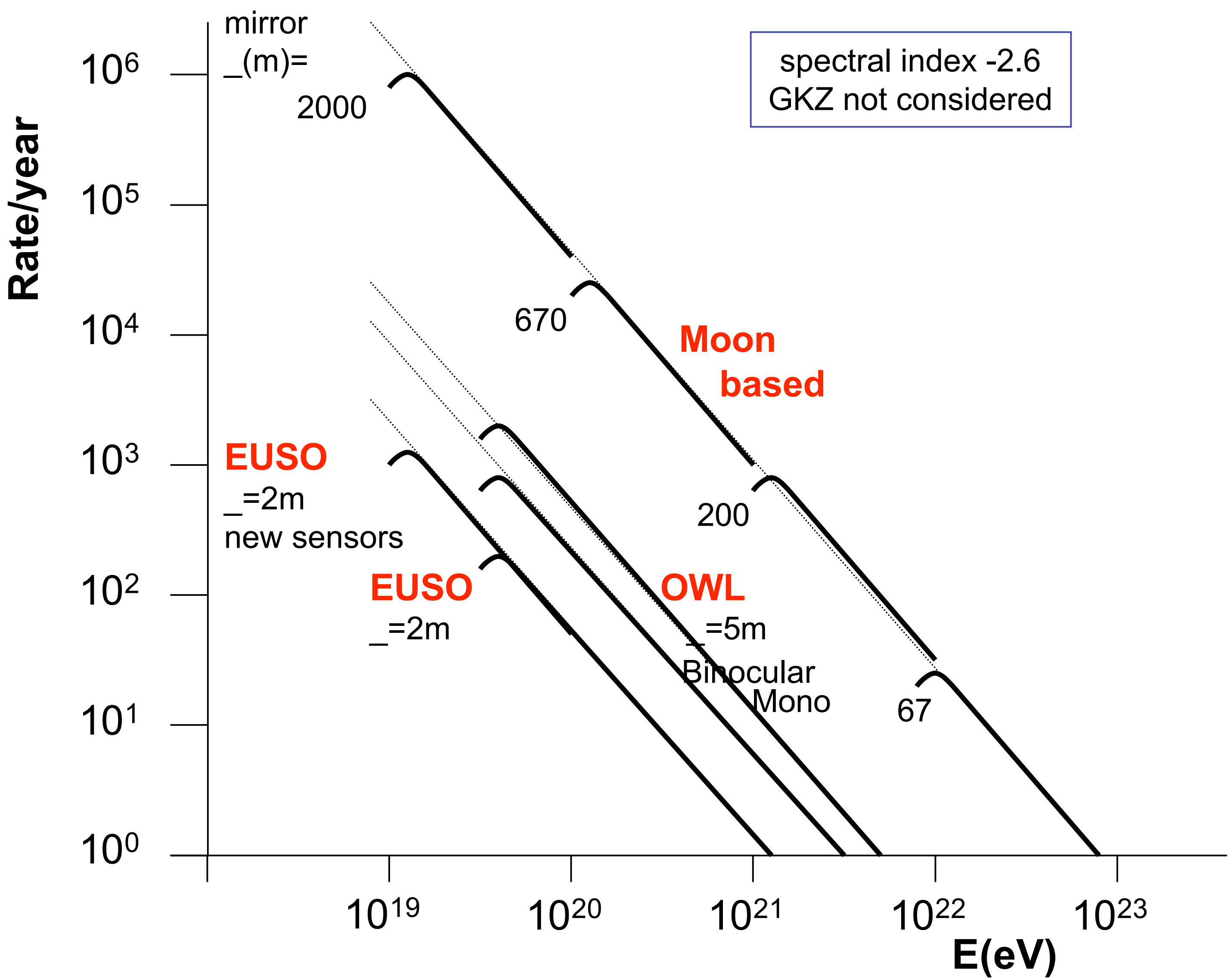
Moon Base: candidate optical configurations

INOA

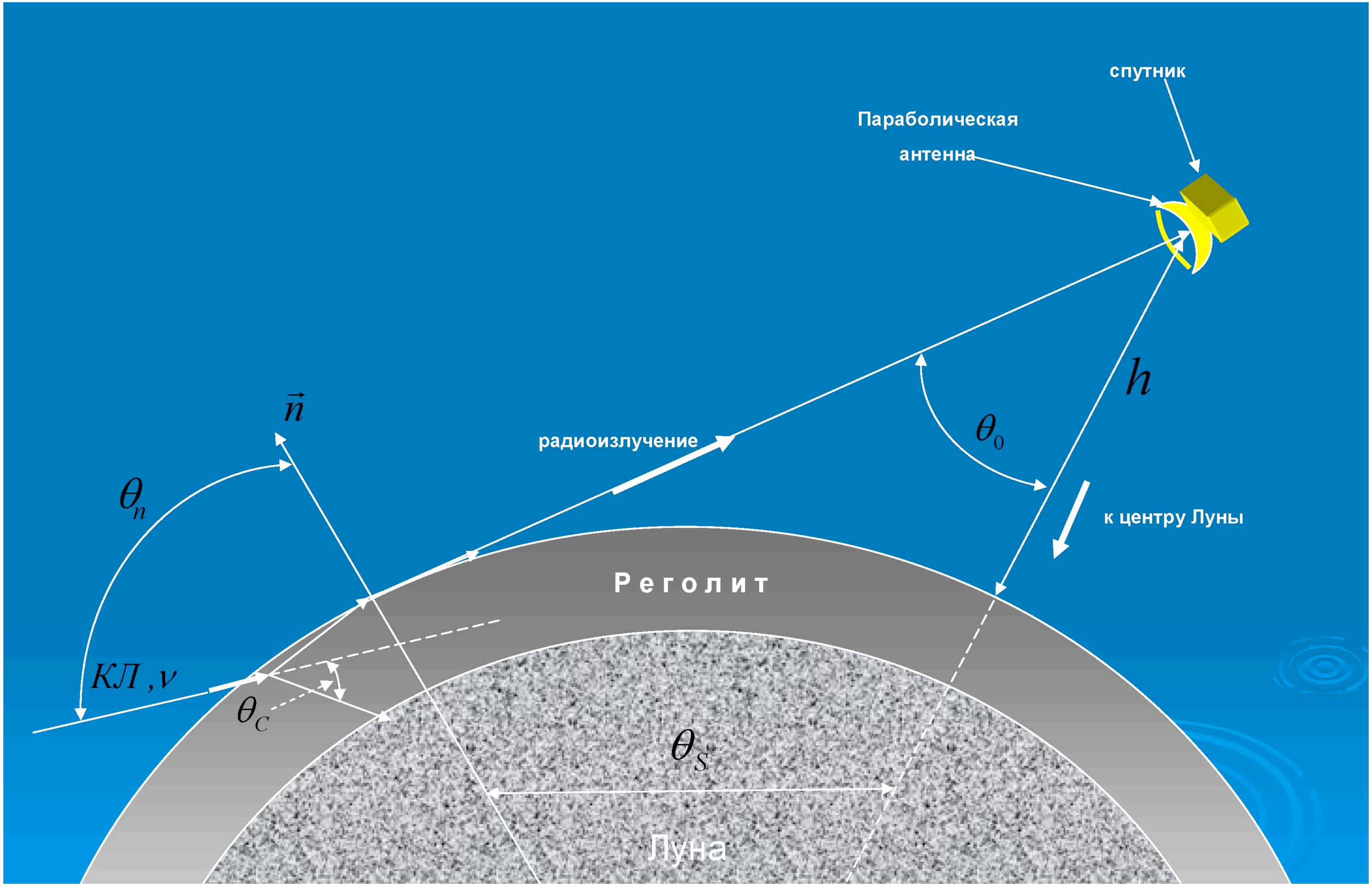


Off axis afocal system

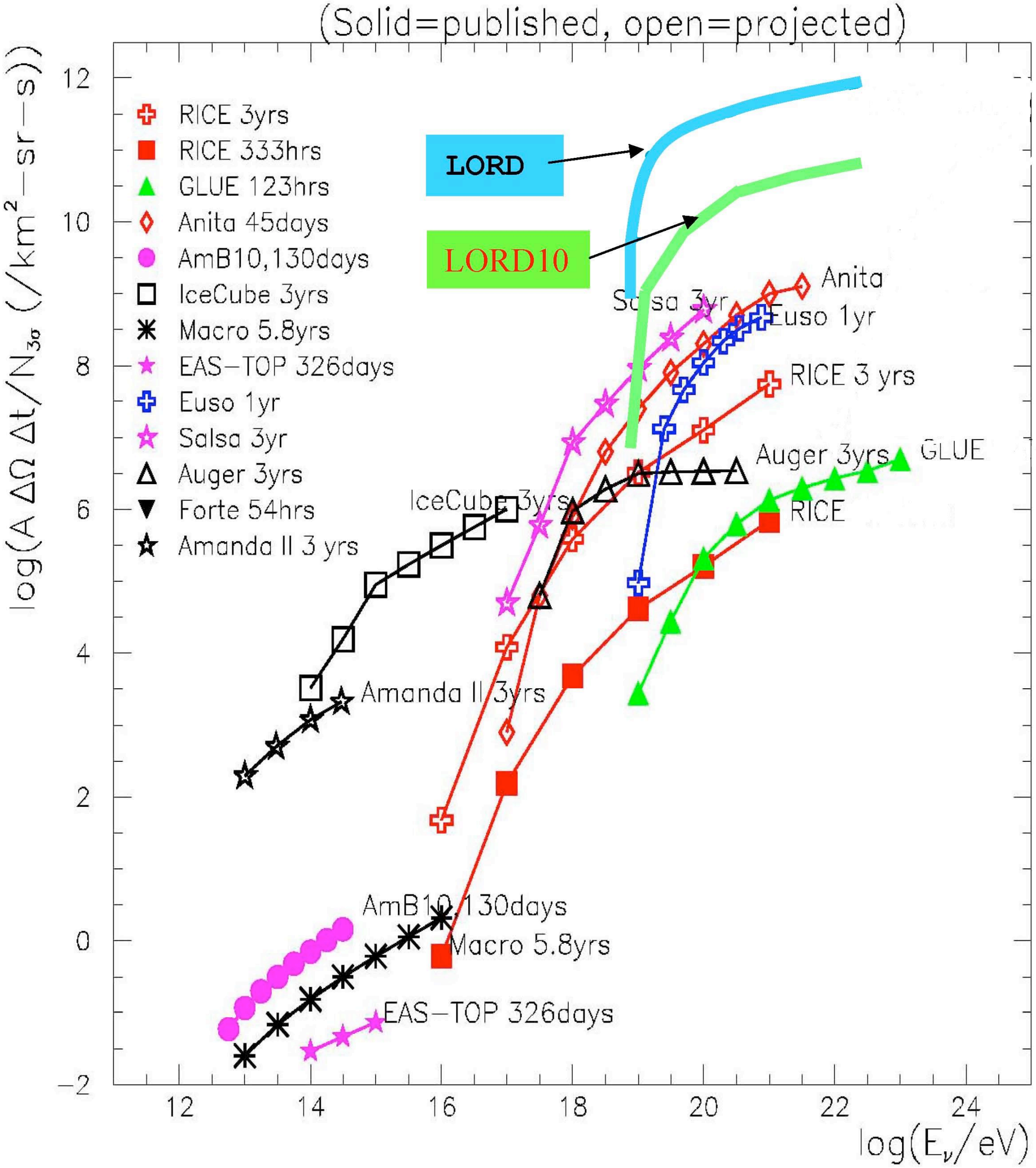
- No obstruction
- Easier system arrangement


mirror
_(m)=
2000
670
200
67
spectral index -2.6
GKZ not considered
Moon
based
EUSO
_=2m
new sensors
EUSO
_=2m
OWL
_=5m
Binocular
Mono
Rate/year
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}
E(eV)

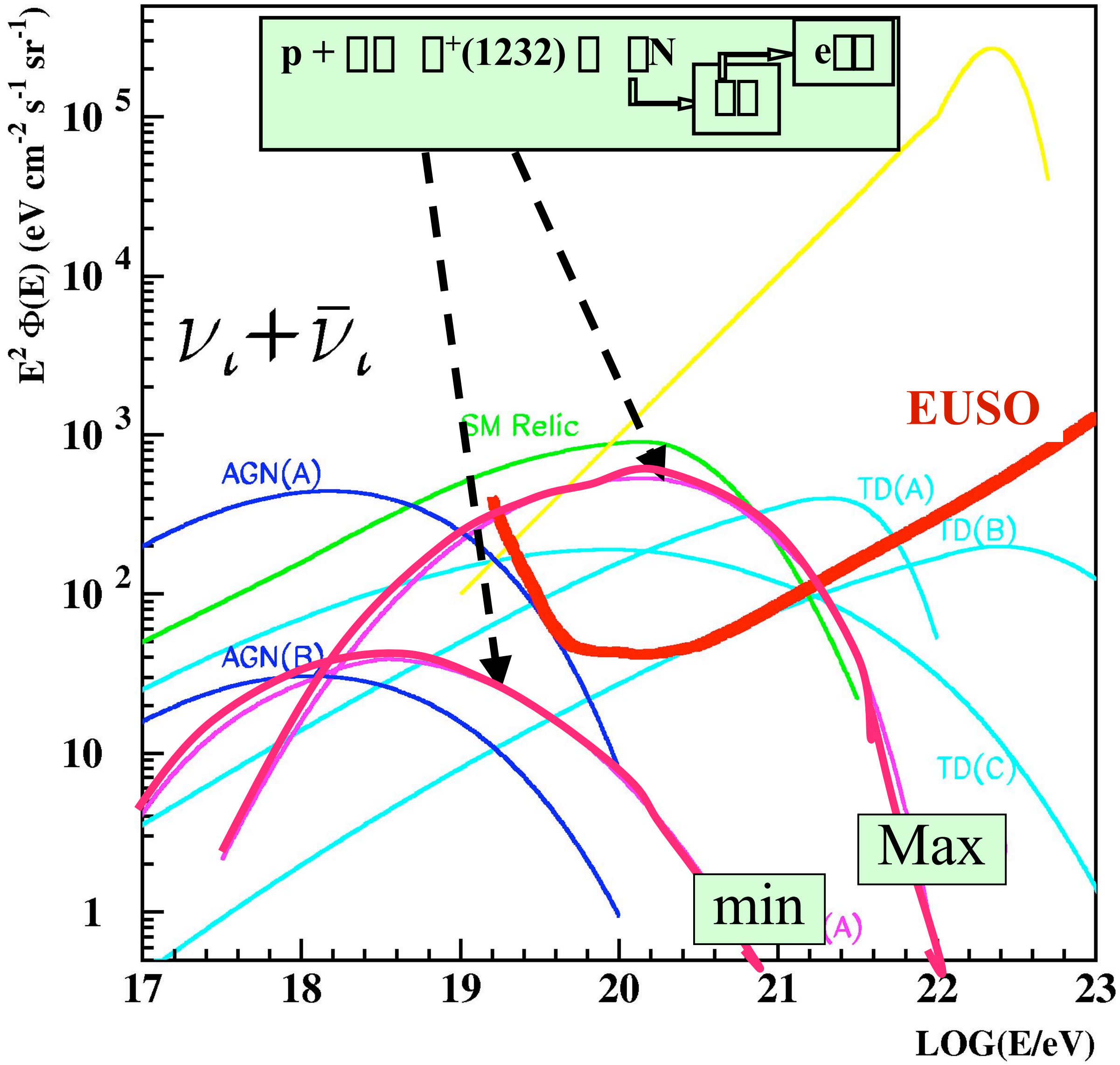
	altitude (10^3km)	pupil of the otics	threshold in energy(eV)	observed area(10^6km^2)	observed mass(10^{12}t)	Duty cycle	effective area (10^6km^{2}sr)
Auger(N+S)	0	--------	≈10^{18}	0.03	0.3	1	0.007
EUSO	0.4	2m	$5x10^{19}$	0.18	1.8	0.1	0.05
EUSO (SiPM)	0.4	2m	$1x10^{19}$	0.18	1.8	0.1	0.05
OWL(binocular)	0.8	5m	$5x10^{19}$	0.50	5.0	0.1	0.3
OWL(2xmono)	0.8	5m	$3x10^{19}$	1.00	10.0	0.1	0.6
Moon Based	400	20m	≈10^{23}	72	720	0.2	144
	400	67m	≈10^{22}	72	720	0.2	144
	400	200m	≈10^{21}	72	720	0.2	144
	400	670m	≈10^{20}	72	720	0.2	144
	400	2000m	≈10^{19}	72	720	0.2	144



спутник
Параболическая
антенна
h
$\vec{n}$
радиоизлучение
θ_0
θ_n
к центру Луны
Реголит
$КЛ, \nu$
θ_C
θ_S
Луна



(Solid=published, open=projected)
RICE 3yrs
RICE 333hrs
GLUE 123hrs
Anita 45days
AmB10,130days
IceCube 3yrs
Macro 5.8yrs
EAS−TOP 326days
Euso 1yr
Salsa 3yr
Auger 3yrs
Forte 54hrs
Amanda II 3 yrs
LORD
LORD10
Anita
Euso 1yr
RICE 3 yrs
Auger 3yrs
GLUE
RICE
IceCube 3yrs
Amanda II 3yrs
AmB10,130days
Macro 5.8yrs
EAS−TOP 326days
log(A ΔΩ Δt/N3σ (/km²−sr−s))
log(Eν/eV)


p + □□ □+(1232) □ □N
e□□
□□
$\nu_\tau + \bar{\nu}_\tau$
SM Relic
AGN(A)
AGN(B)
TD(A)
TD(B)
TD(C)
EUSO
Max
min
(A)
E^2 Φ(E) (eV cm^{-2} s^{-1} sr^{-1})
LOG(E/eV)
1
10
10 2
10 3
10 4
10 5
17
18
19
20
21
22
23

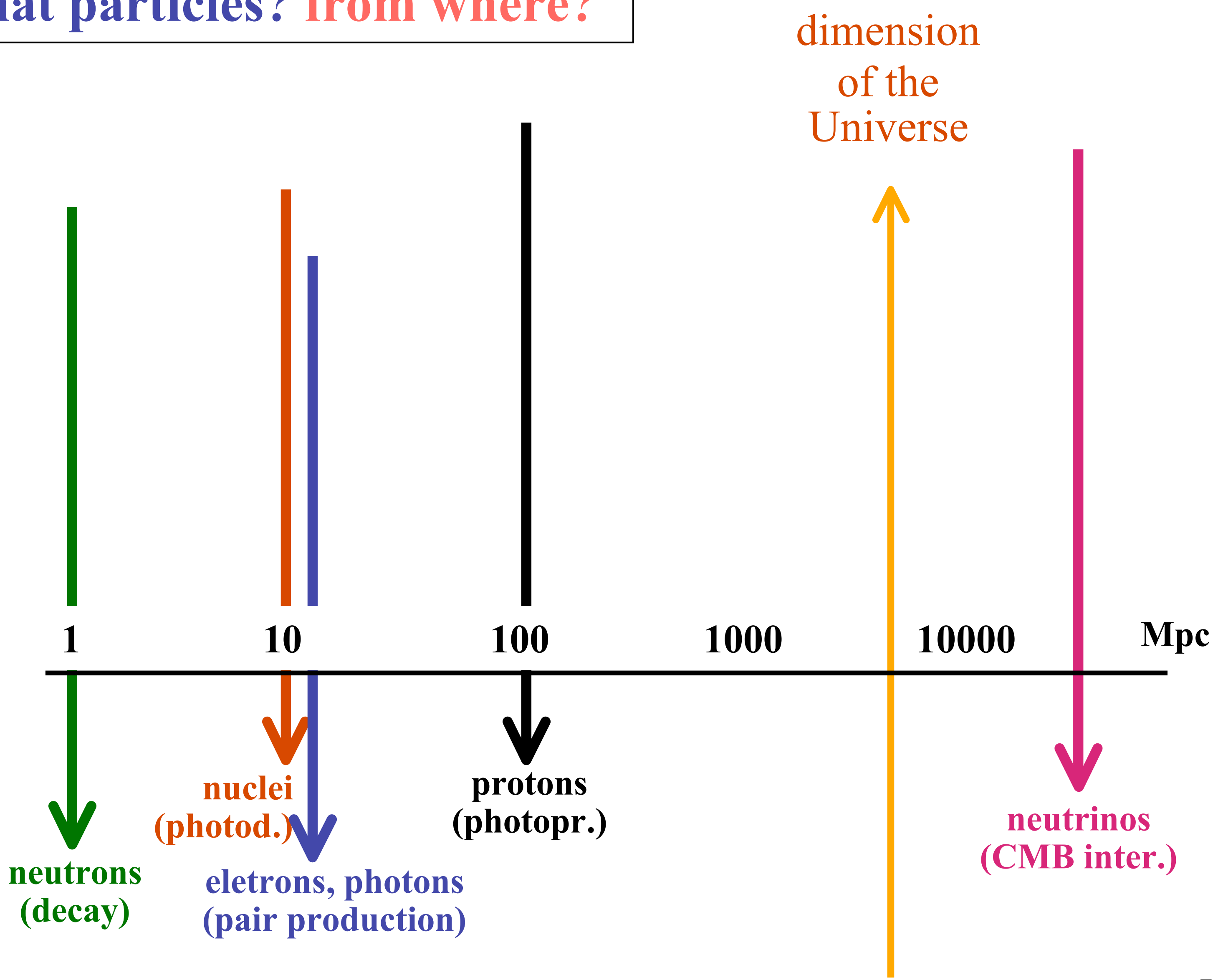
A new actor on the scene of CR from space?

neutrino

new instrument for
Astrophysics,
Cosmology,
Particle Physics

$E_{particle} = 10^{20}$ eV

what particles? from where?



Conclusions

High Z: Heavy Nuclei eXplorer (HNX) [exp. ENTICE ed ECCO] in 'stand by'
possible only on the Moon surface

Isotopes (E>GeV/n): on Earth orbit □80 are accessible but no plans exist
light isotopes from PAMELA and AMS in next years
high rate assured on the Moon up to very high E

Rare components: antiN/N up to <10^{-9} (AMS)
antip, e+ up to a >200 GeV (PAMELA ed AMS)
electrons up to >3 TeV (PAMELA, AMS, CALET)
1-10 TeV region on reach on the Moon surface

Elemental composition: up to 100 TeV by ballooning (going on)
up to 1 PeV in orbit (several projects and concepts)
up to 100 PeV (well behind the knee) on the Moon

Ultra High Energies: up to few * 100 EeV on Earth surface (going on)
up to 1000 EeV from orbit (but EUSO in 'stand by')
up to a few 10 ZeV from the Moon surface,
also higher from Moon orbit
a UHE Neutrino Observatory ($E_{□}$>10^{19}) is feasible