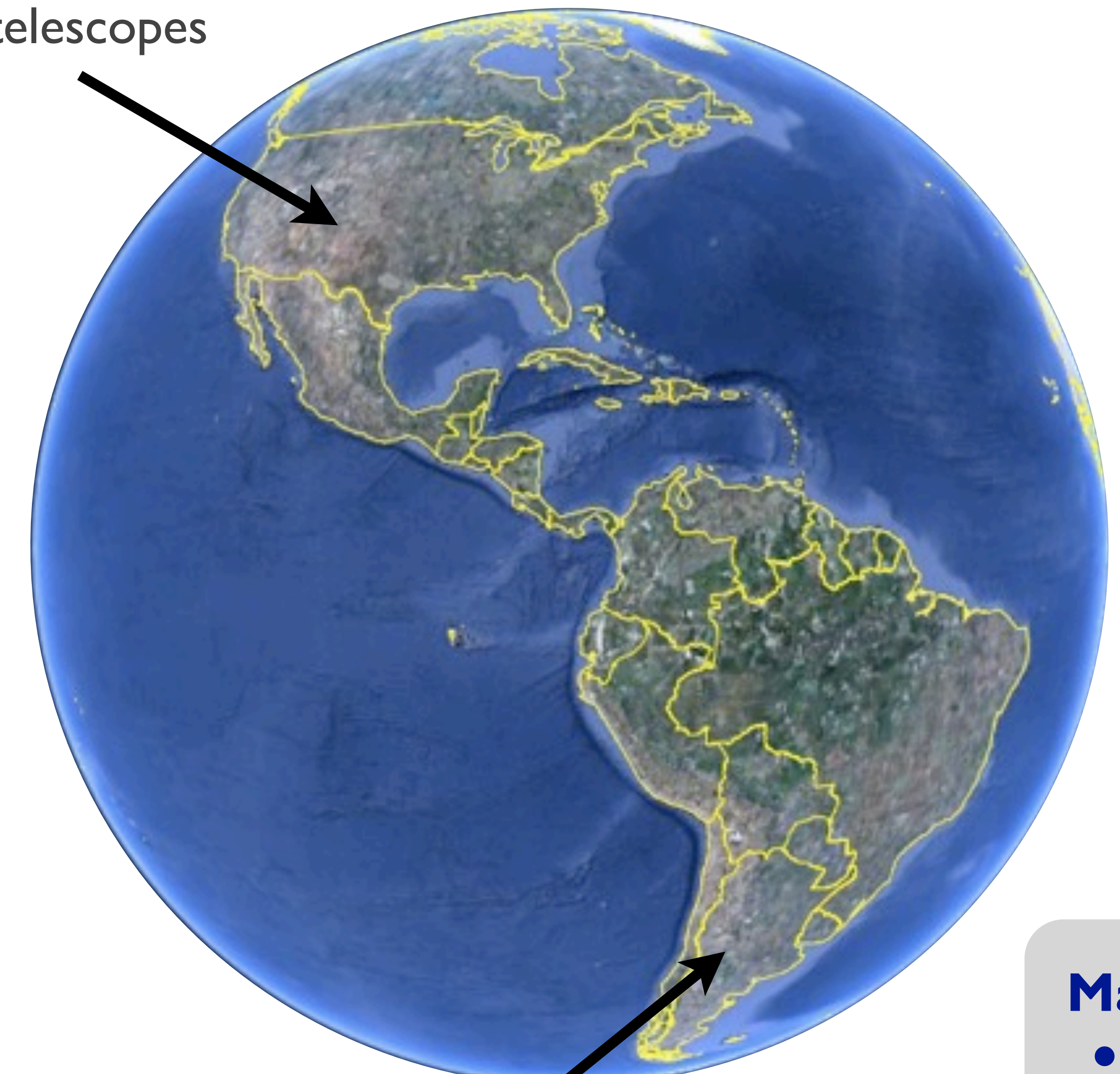
The Pierre Auger Observatory

Ralph Engel, for the Pierre Auger Collaboration

Auger-North (planned)
4400 detector stations, 20,000 km^2
39 fluorescence telescopes



Aim: sources, propagation and interaction of UHECR

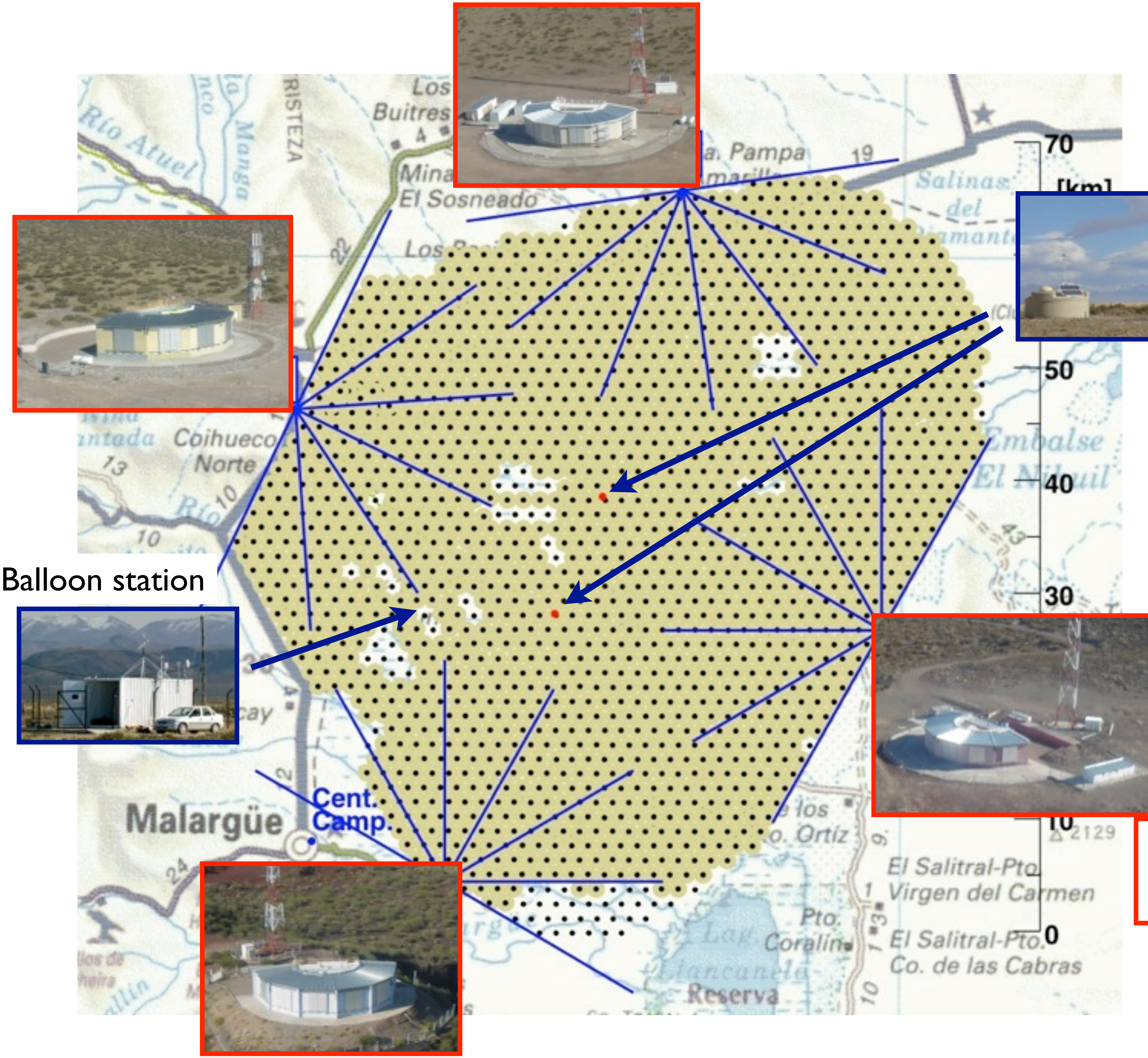
1992 Paris workshop
1996 Design report
(two sites, full sky coverage)

1999 Ground breaking
2001 Engineering array
2003 Construction phase
2008 Auger-South completed

Auger-South (completed)
1600 detector stations, 3,000 km^2
24 fluorescence telescopes

Main physics results:
- **Flux suppression similar to GZK effect**
- **Anisotropy E > 6 10^{19} eV**
- **Acceleration sources favoured**
- **Mixed/heavy elemental composition**
- **Tests of hadronic interactions**

Southern Pierre Auger Observatory



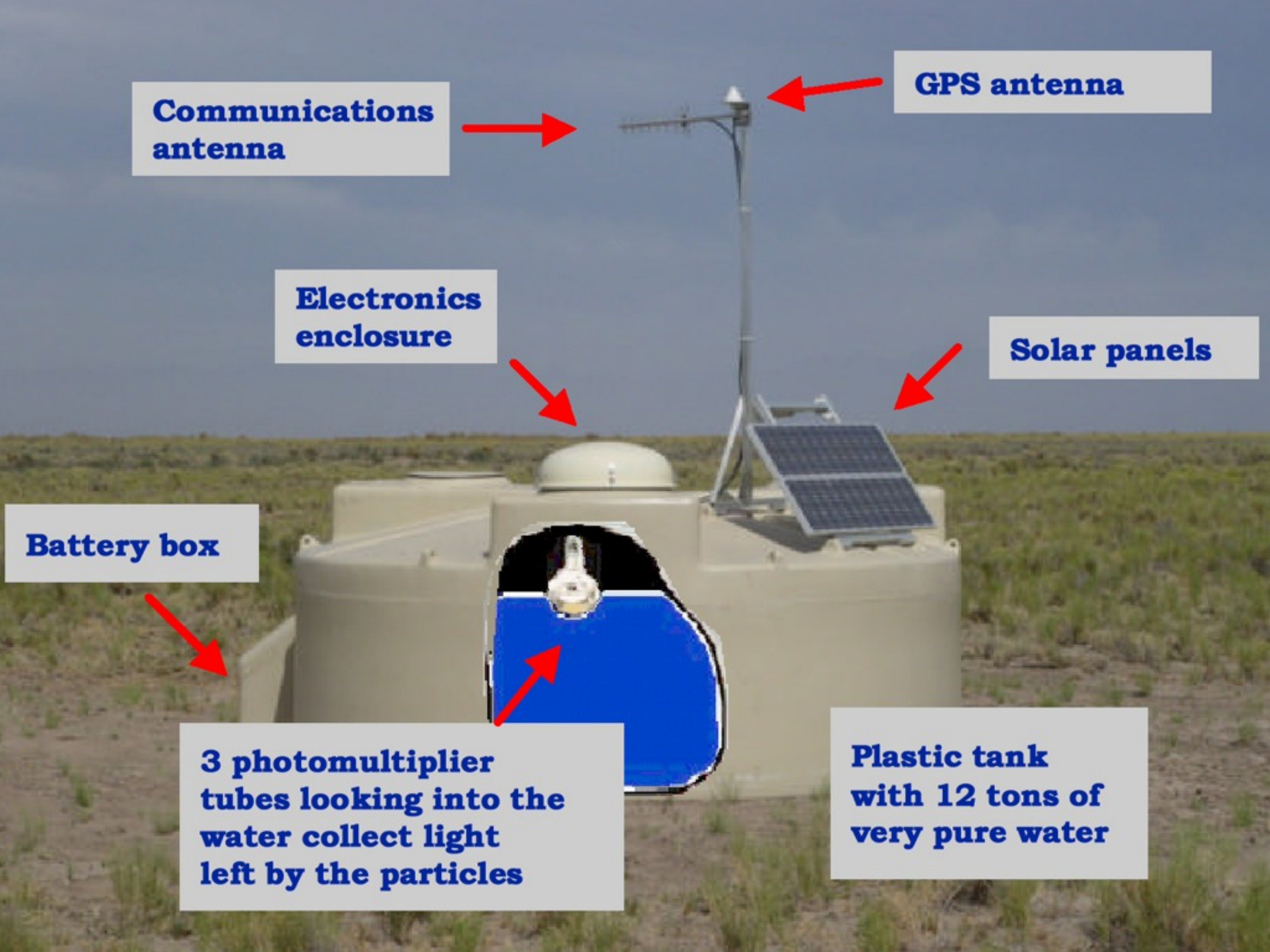
Balloon station

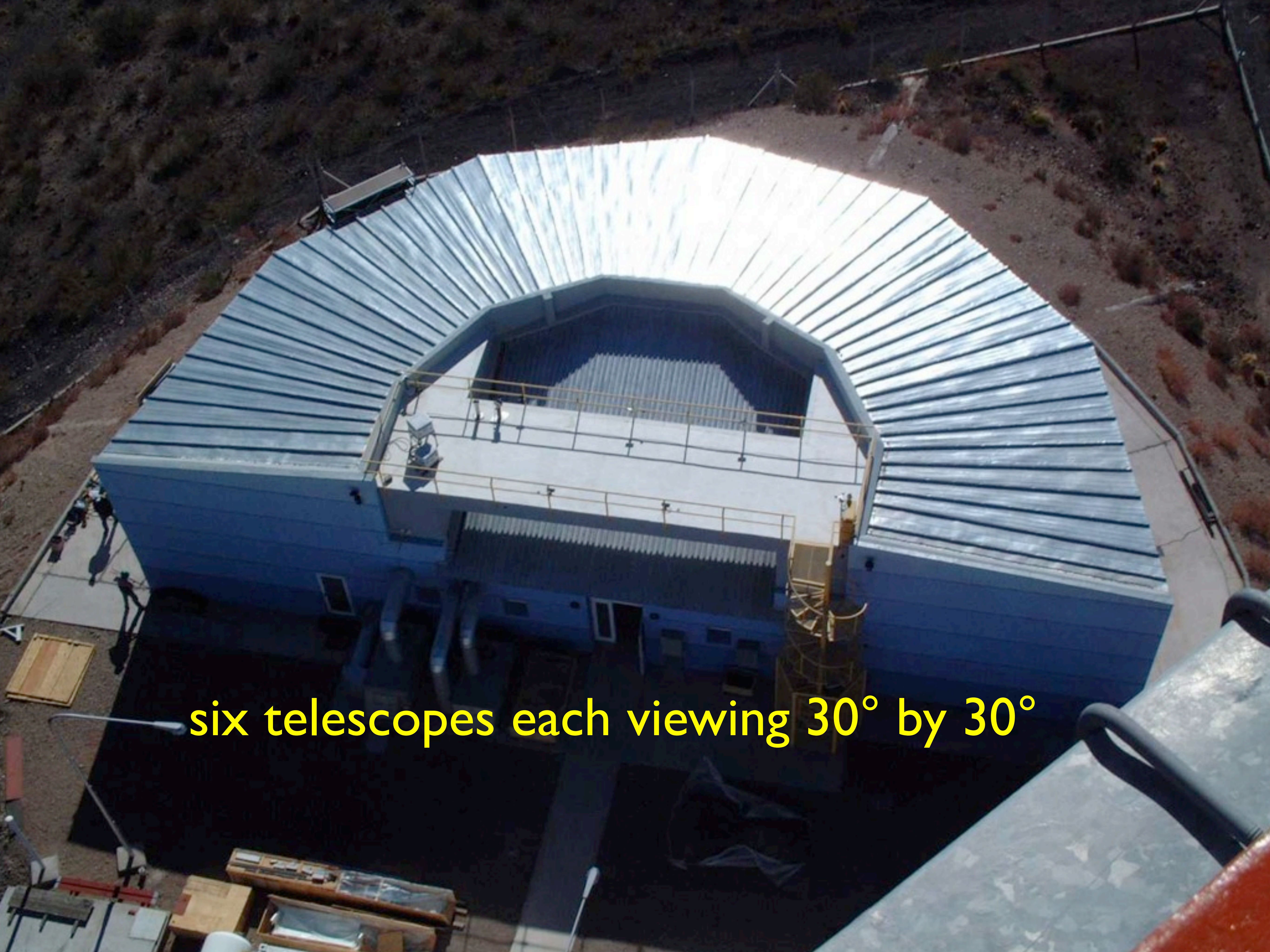
Laser facilities

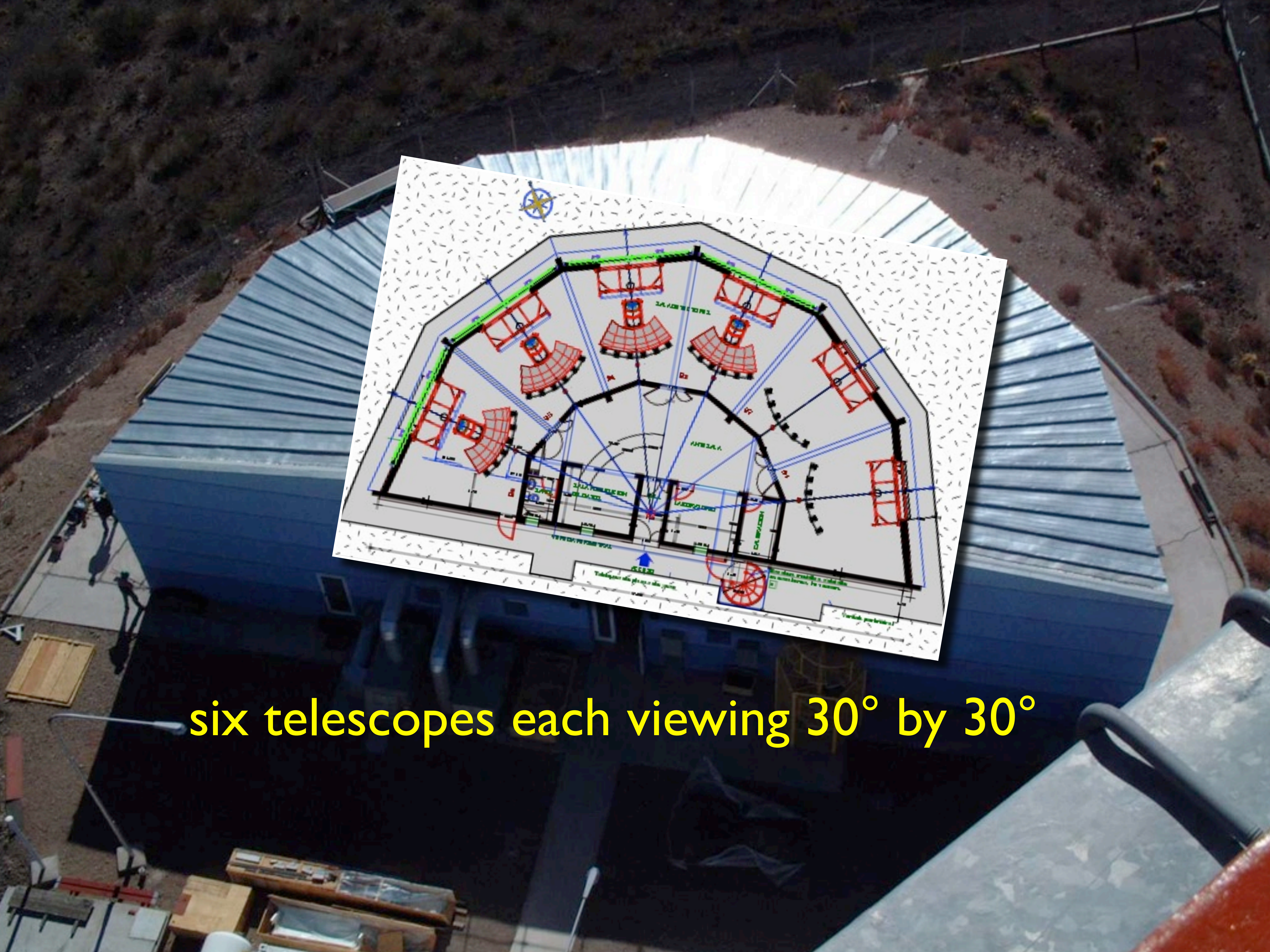
1663 surface detectors: water-Cherenkov tanks (triang. grid of 1.5 km)

4 fluorescence detectors (24 telescopes in total)

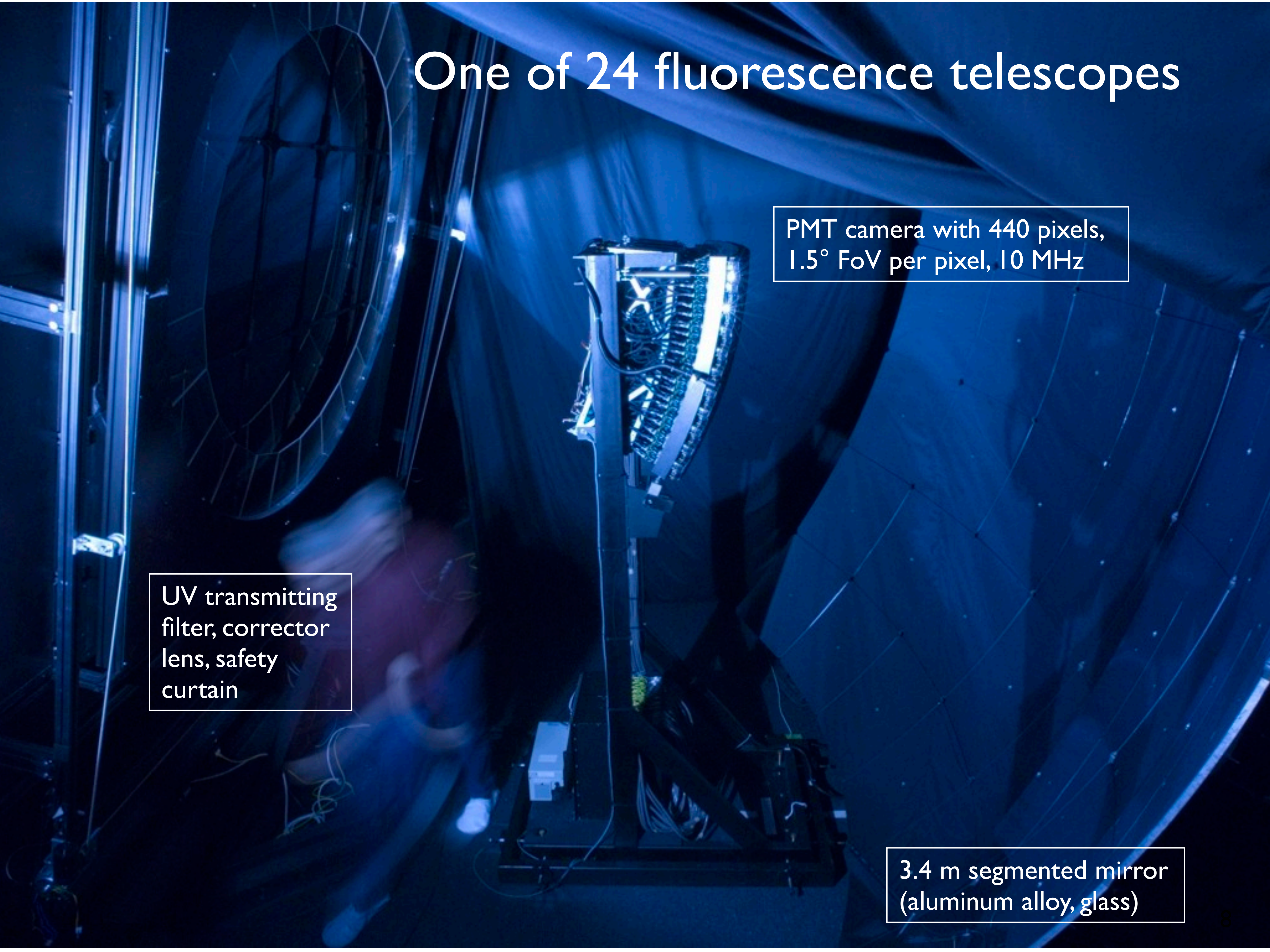
“Last Friday, June 13th, at 13:00 hs, the "last" surface detector (the one with signatures from the whole Collaboration) was filled with water. It was put to work immediately afterwards.”

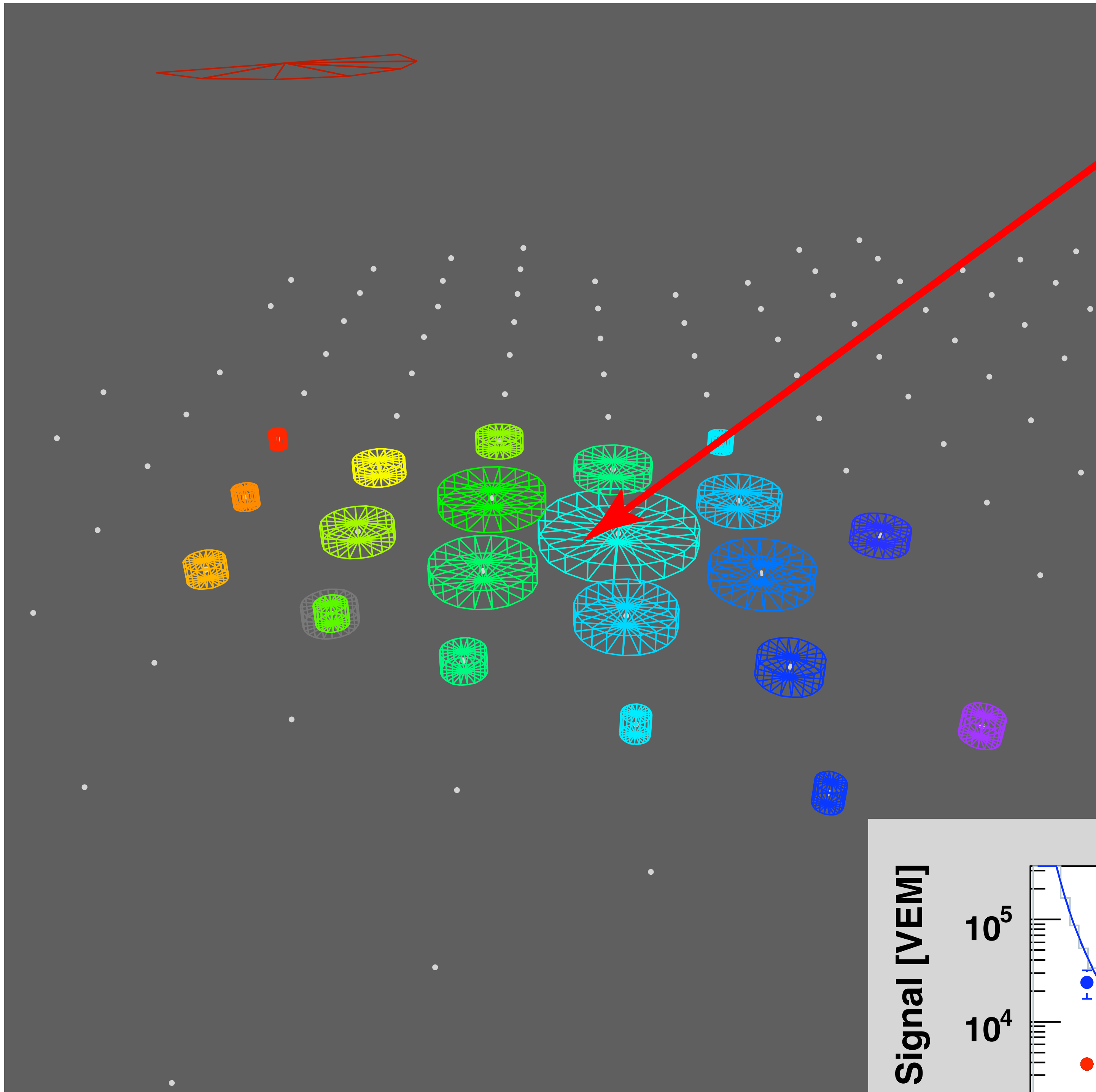

Communications antenna
GPS antenna
Electronics enclosure
Solar panels
Battery box
3 photomultiplier tubes looking into the water collect light left by the particles
Plastic tank with 12 tons of very pure water


six telescopes each viewing 30° by 30°


six telescopes each viewing 30° by 30°

One of 24 fluorescence telescopes

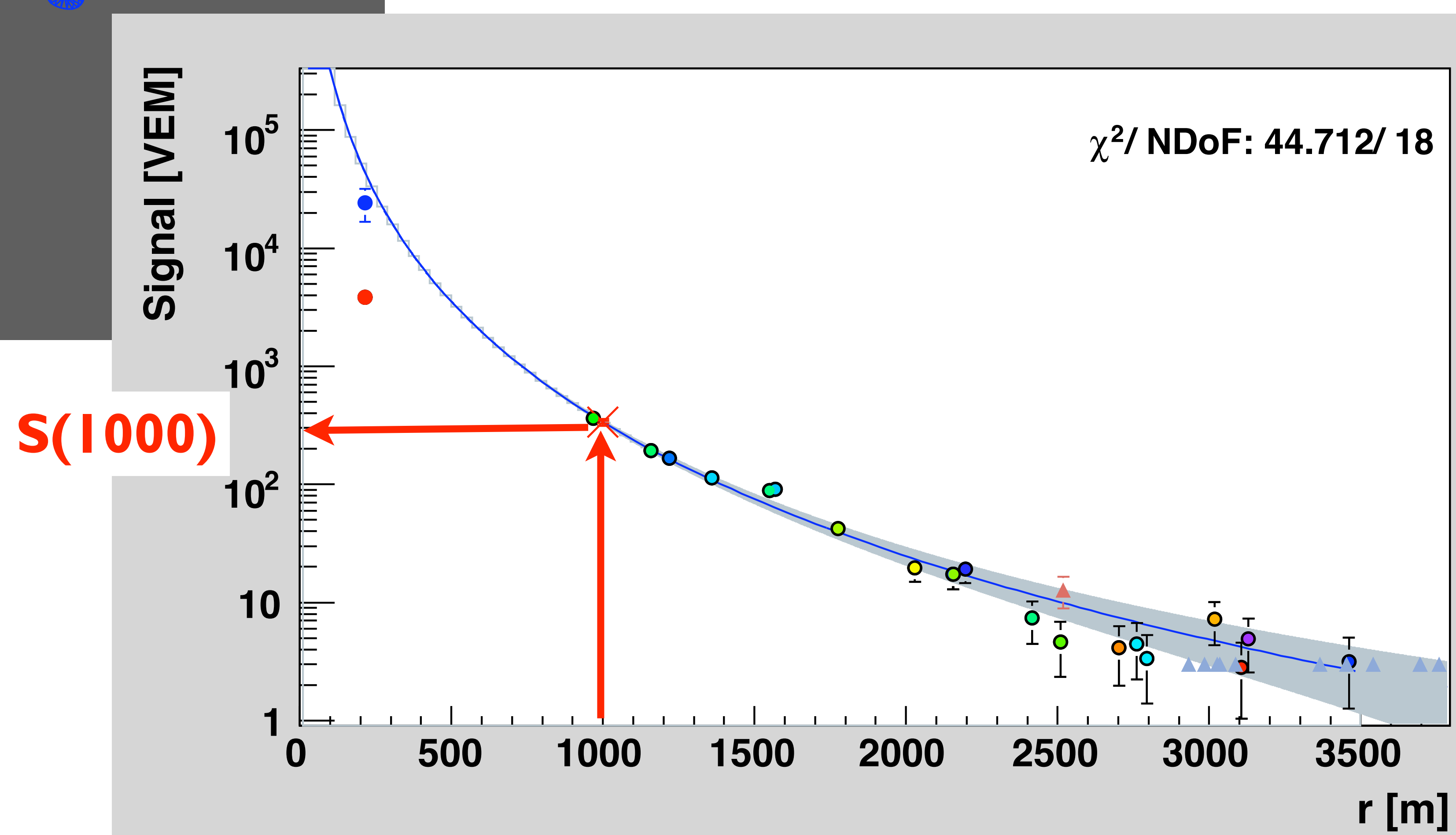




Surface detector events

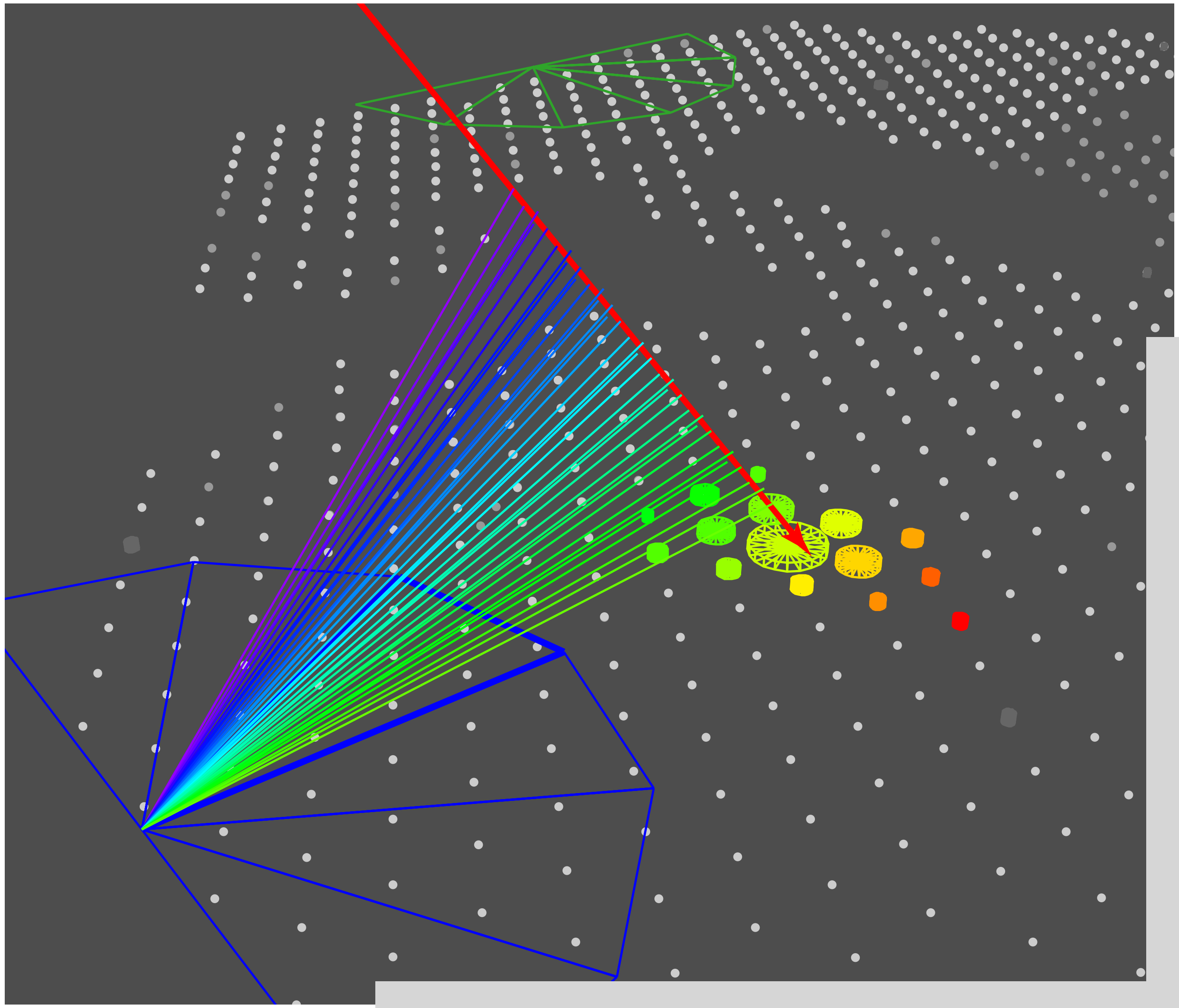
More than 650,000 events
(T5 trigger, used in analysis)

Example: E > 10^{20} eV, $\theta \approx 45°$

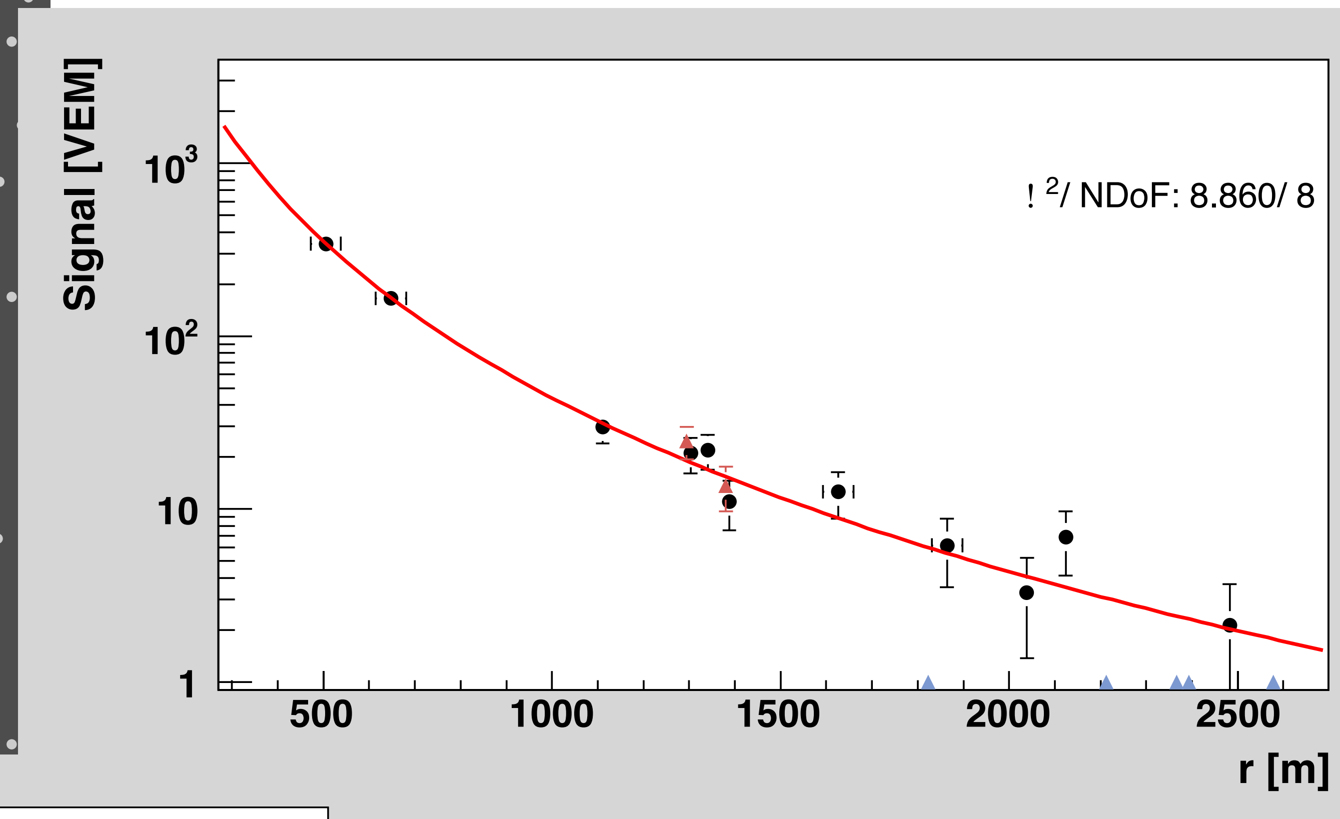


Tank signal in units
of the signal of
a vertical muon

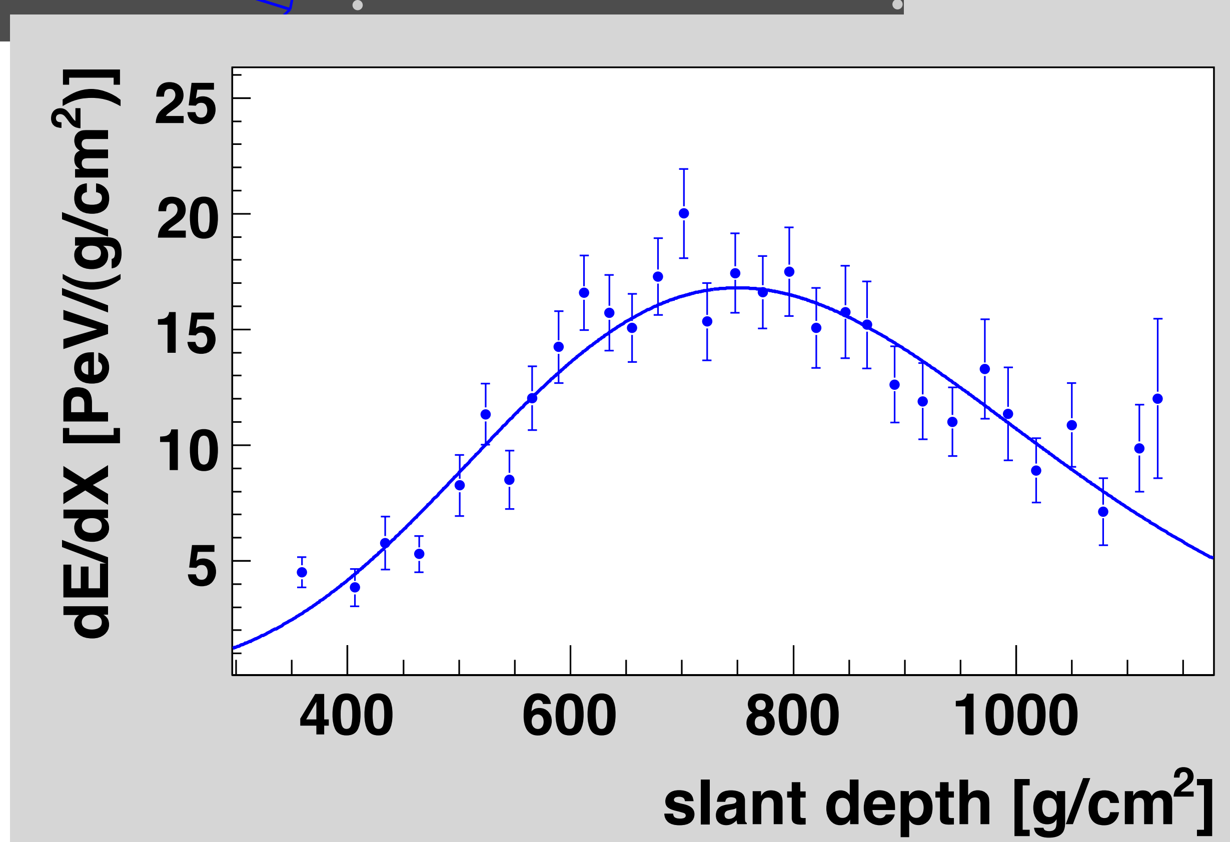
Golden hybrid events



Lateral distribution

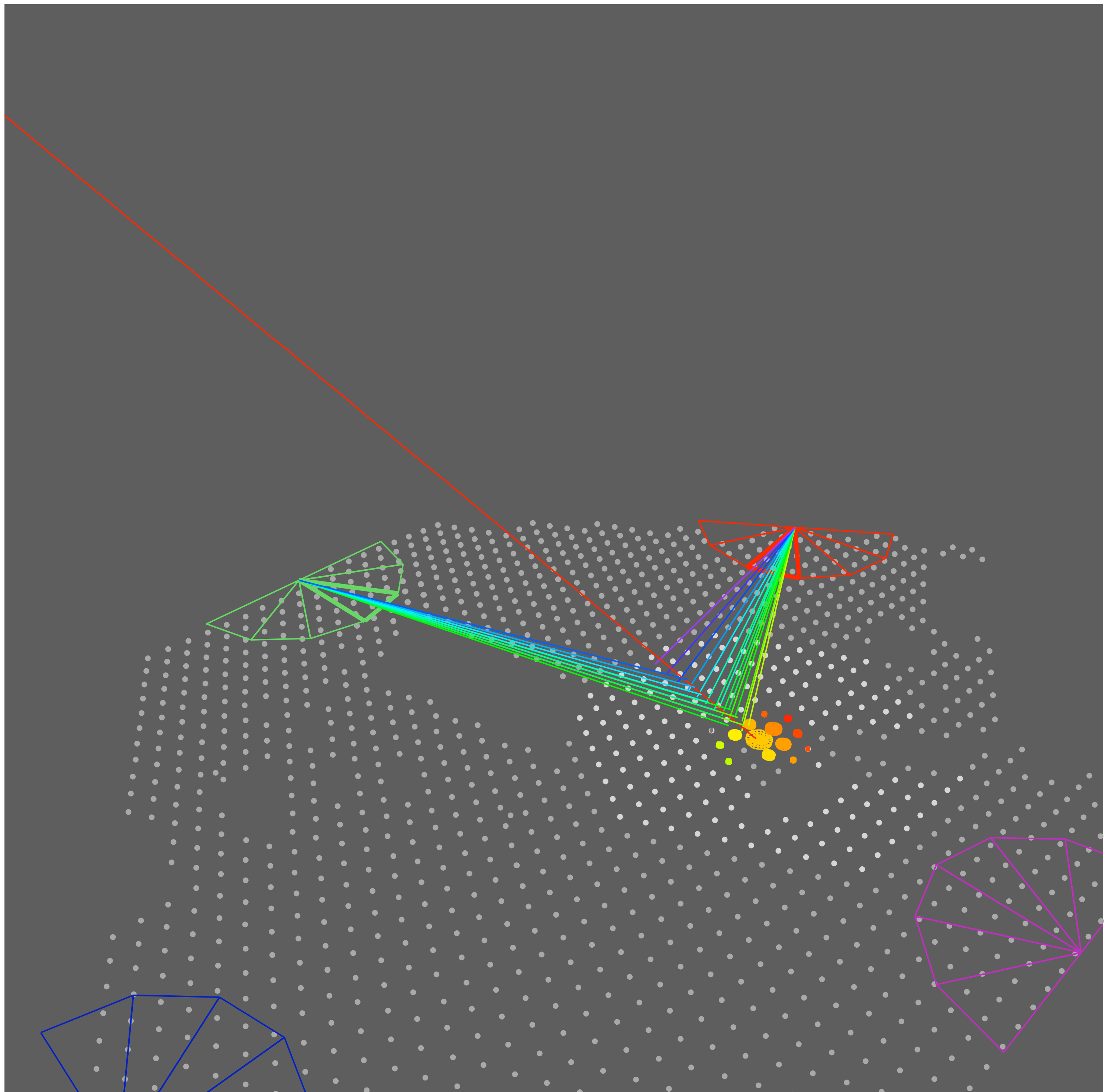


Shower longitudinal profile



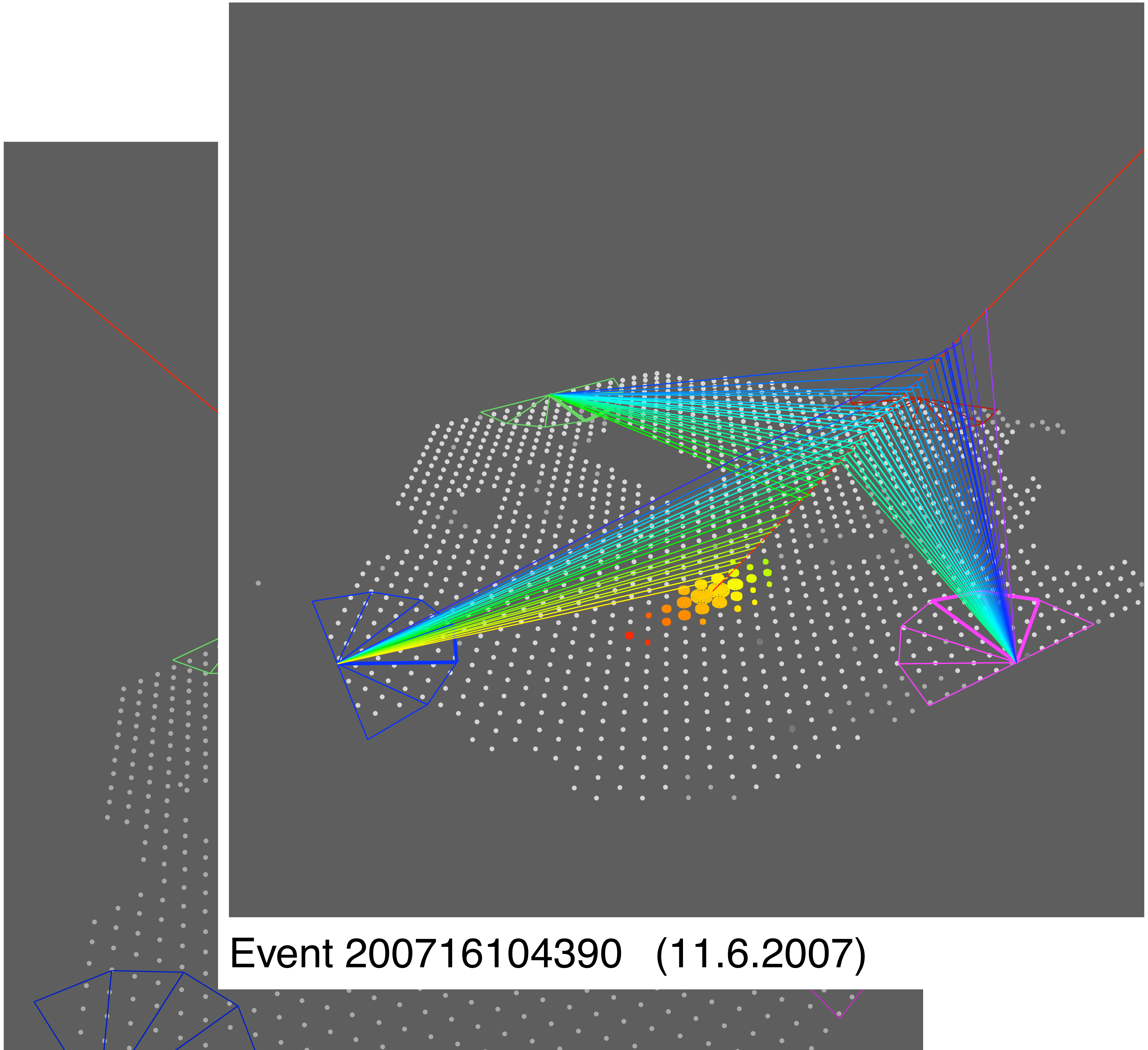
Combination of information from longitudinal and lateral shape possible

Other types of Auger events



Event 200718905882   (9.7.2007)

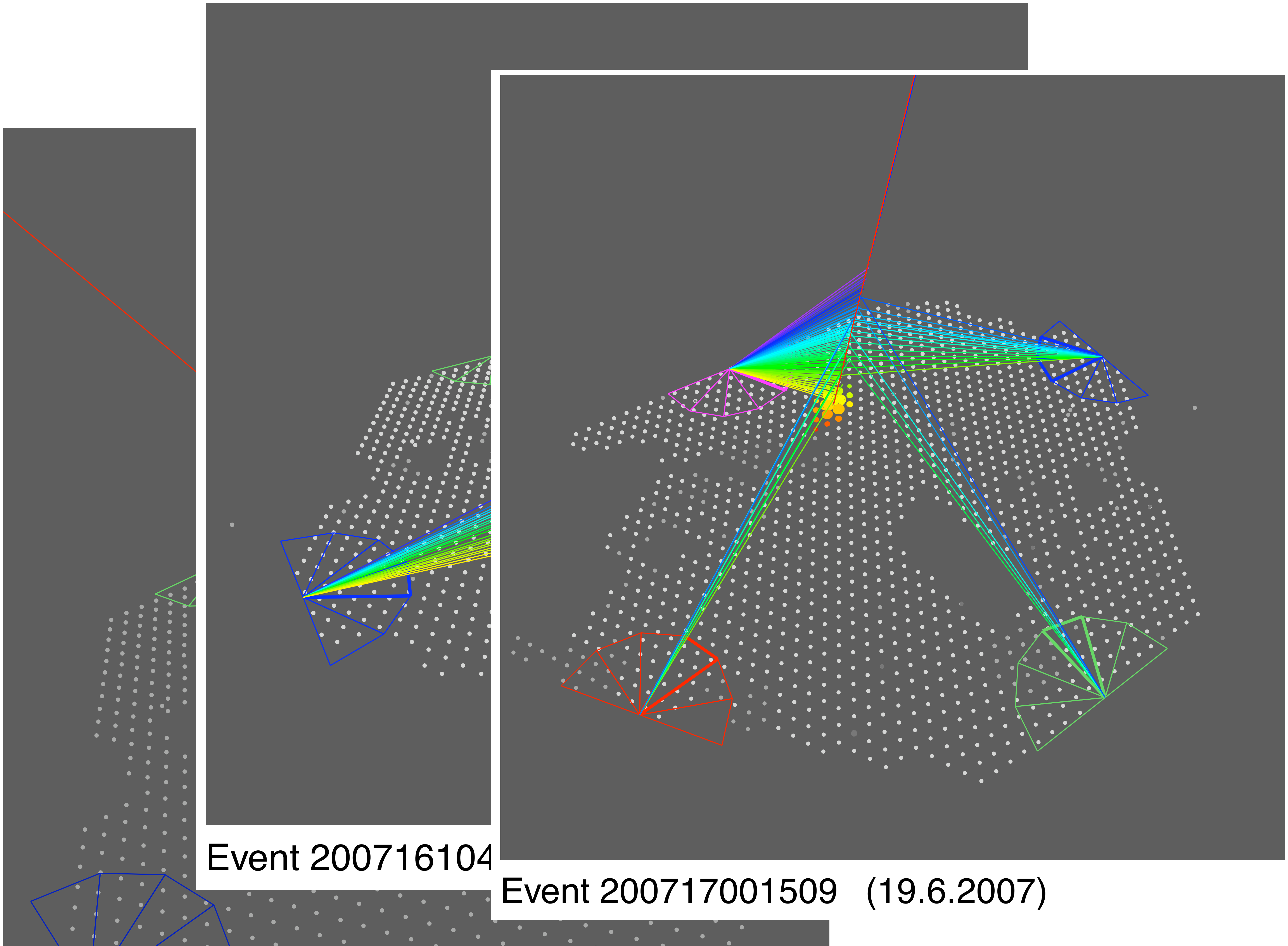
Other types of Auger events



Event 200716104390   (11.6.2007)

Event 200718905882   (9.7.2007)

Other types of Auger events

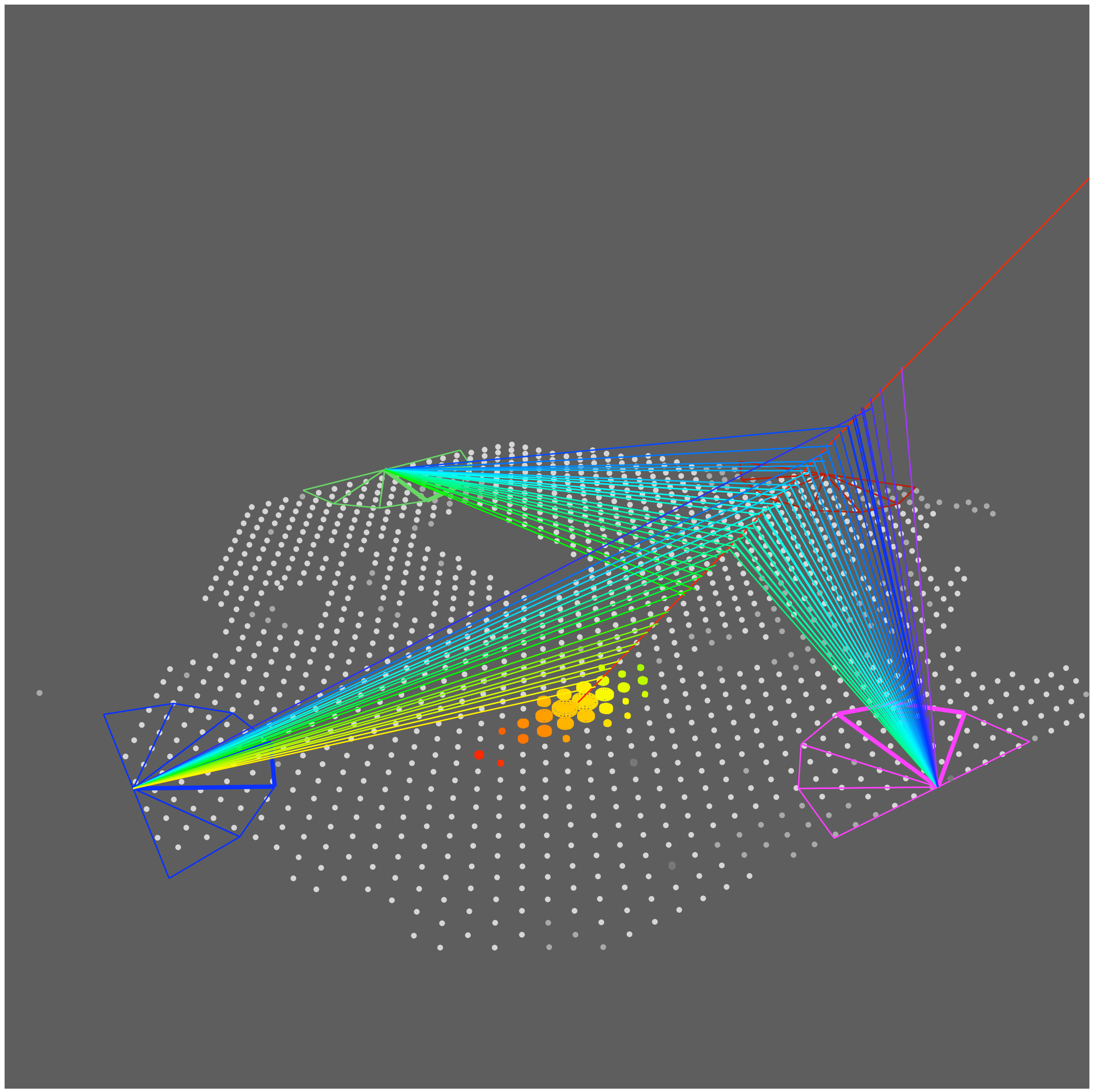


Event 200716104

Event 200717001509   (19.6.2007)

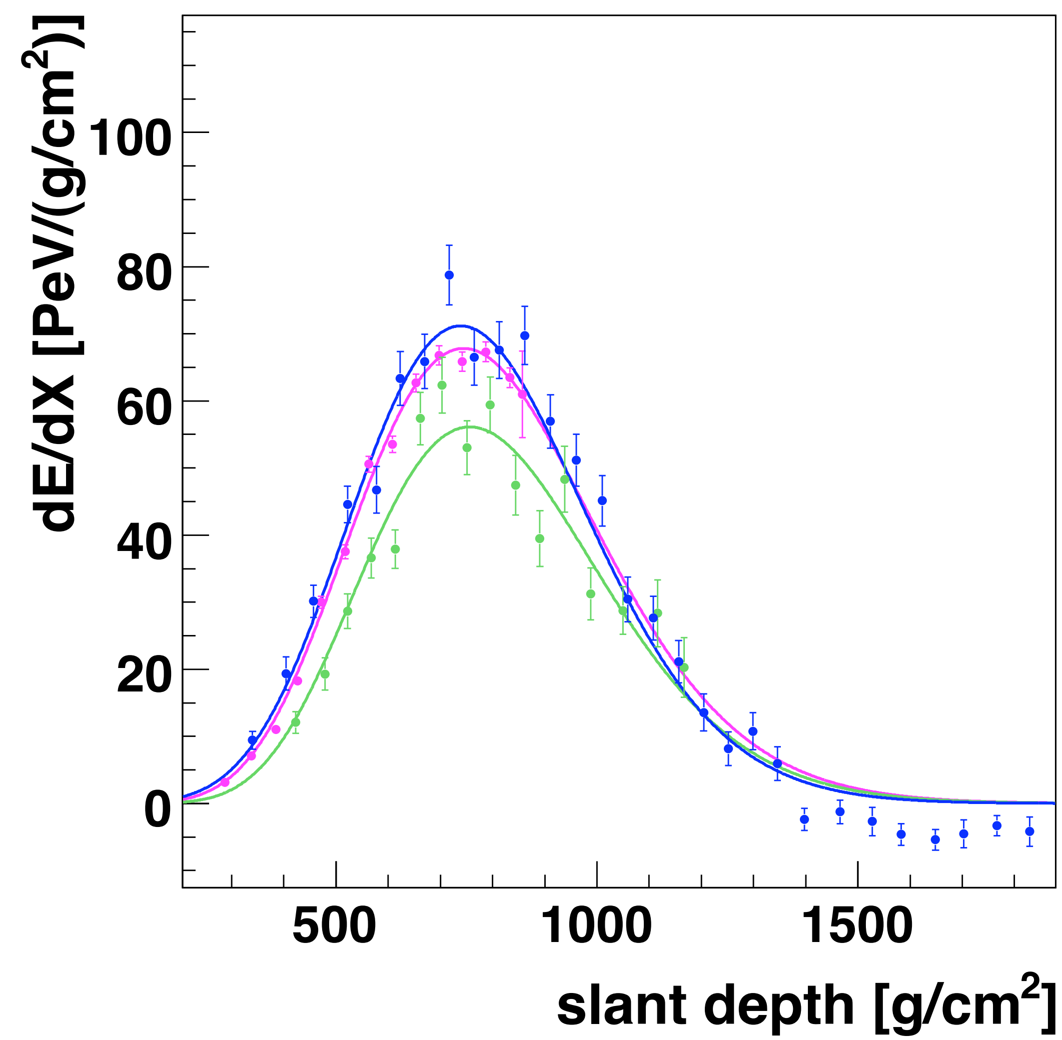
Event 200718905882   (9.7.2007)

Golden hybrid events: many cross checks possible



Event 200716104390 (11.6.2007)

Independent profile reconstuctions

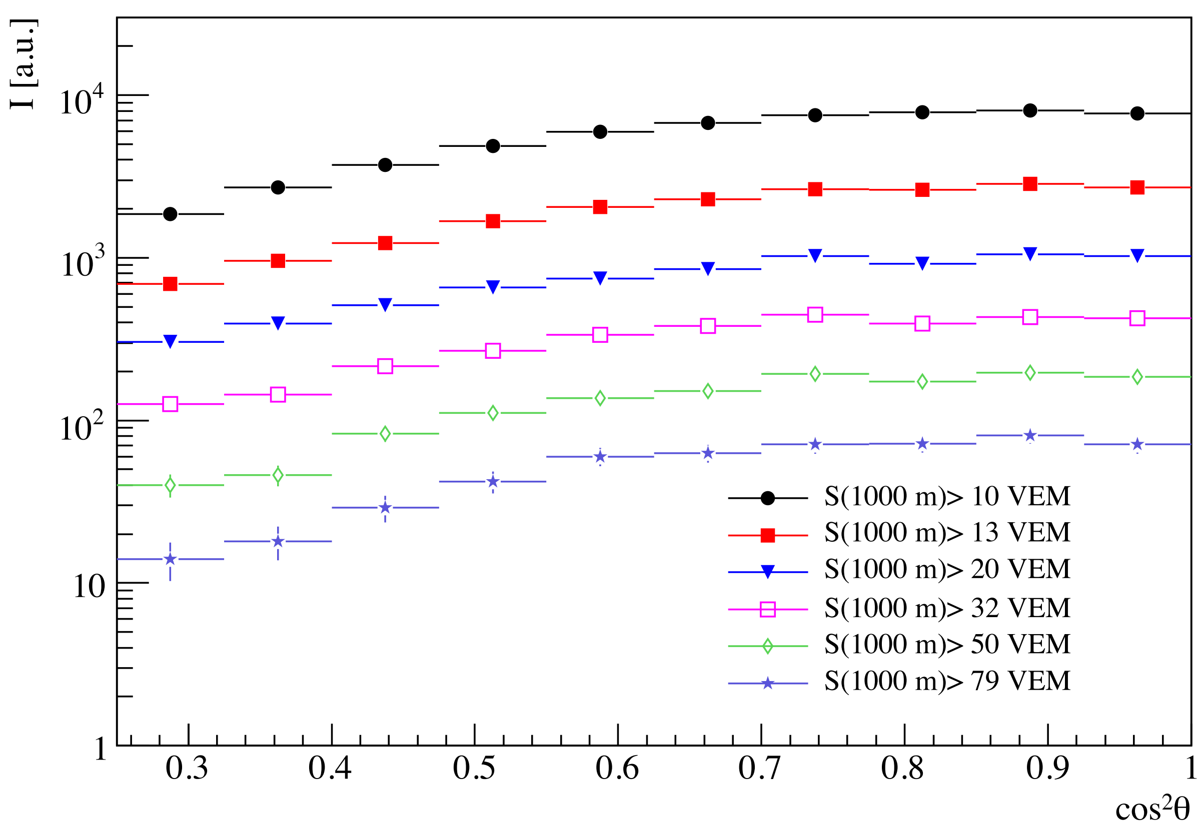


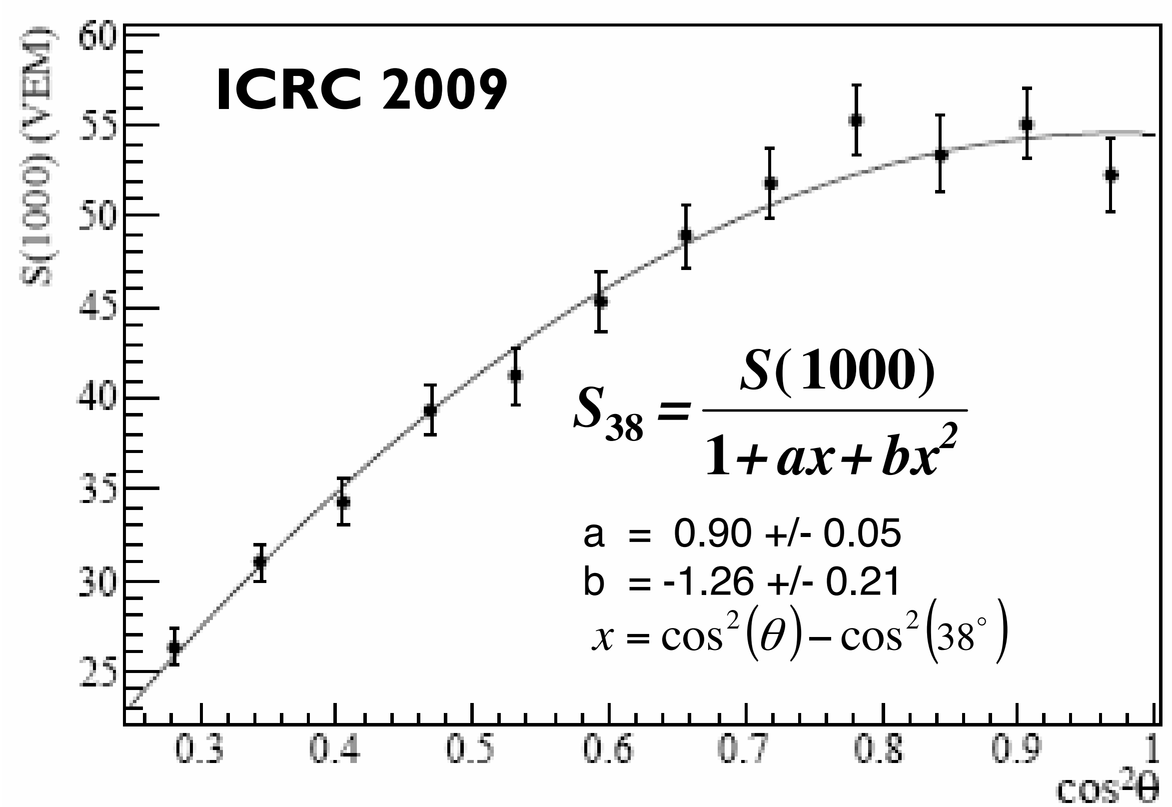
Energy spectrum

Constant intensity cut method

$$N_{\mathrm{ev}} = \int_{\mathrm{angle}} \int_{\mathrm{area}} \int_{\mathrm{time}} \Phi(E,\theta,\varphi) \sin\theta \mathrm{d}\theta \mathrm{d}\varphi \cos\theta \mathrm{d}A \mathrm{d}t$$

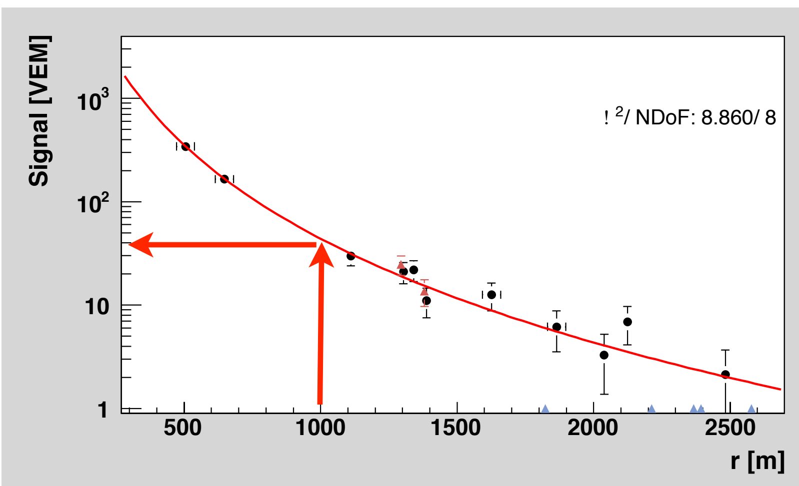
$$\left. \frac{\mathrm{d}N_{\mathrm{ev}}}{\mathrm{d}\sin^2\theta} \right|_{S(1000) > S_{38} f(\theta)} = \mathrm{const.}$$

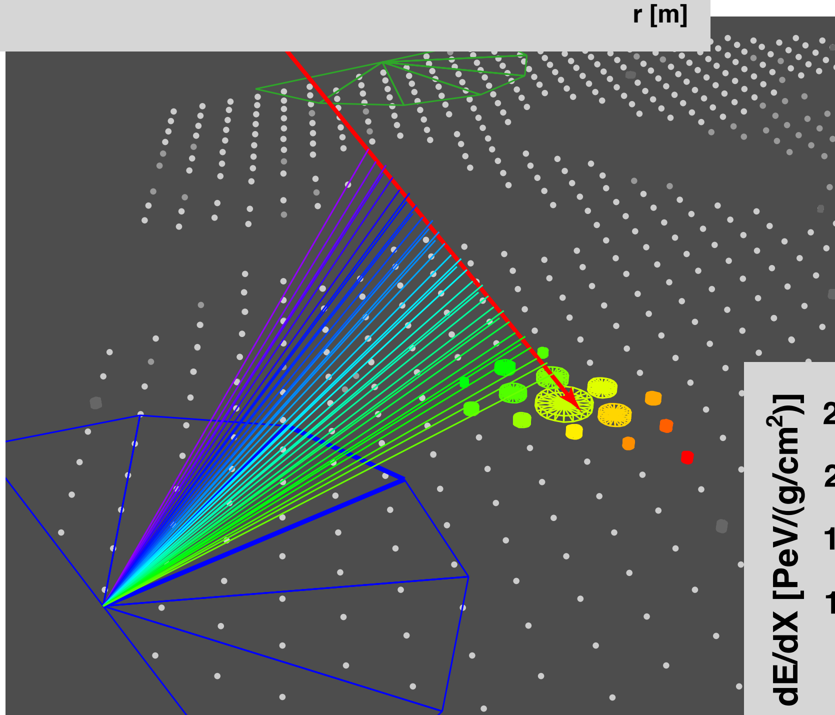


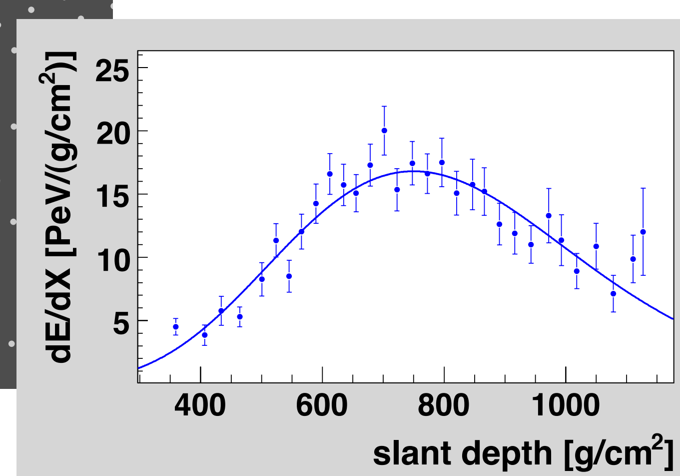


Conversion function independent of S(1000) within statistical uncertainties

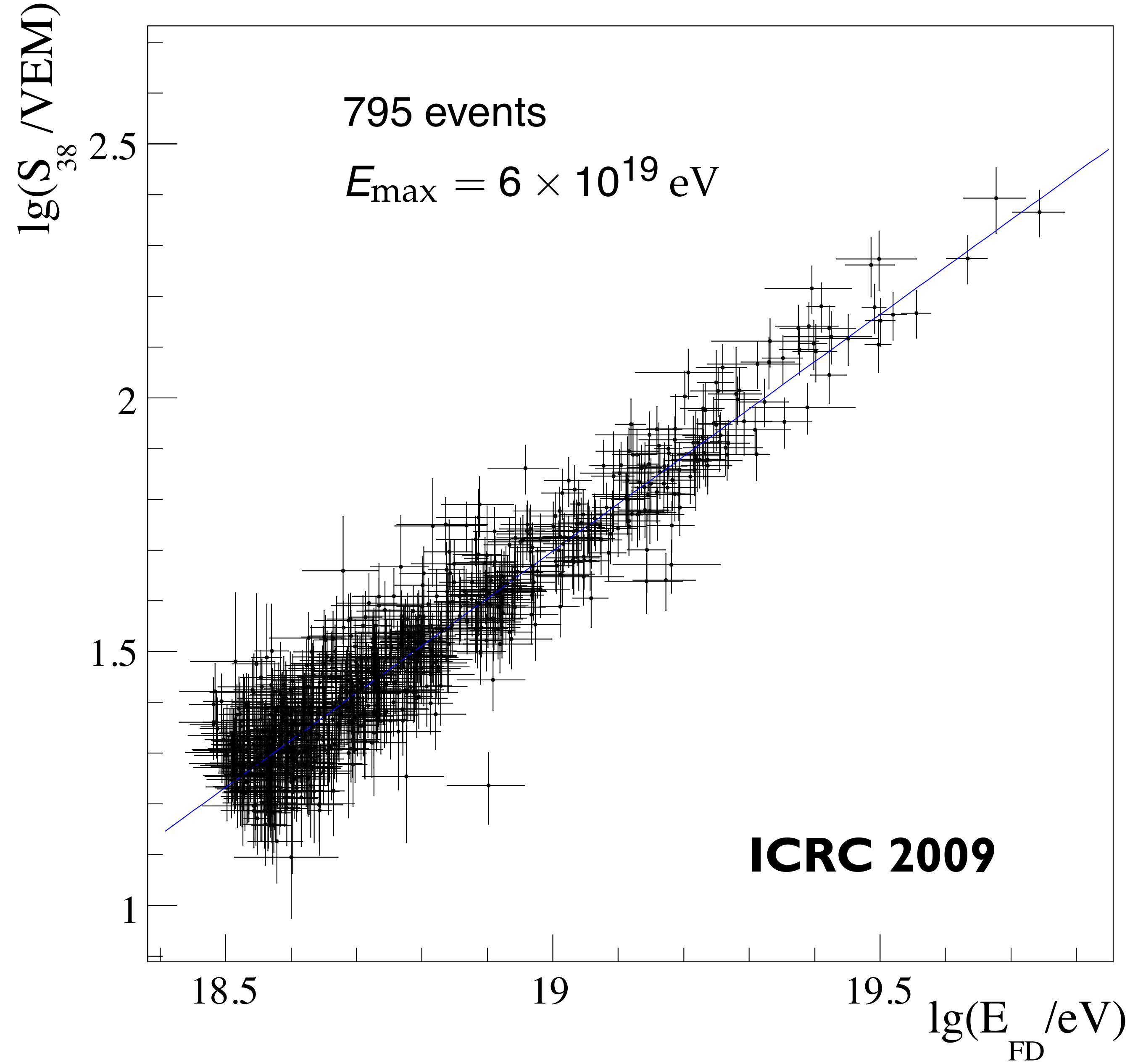
Energy calibration of surface detector







Shower size at 1000m and θ=38°

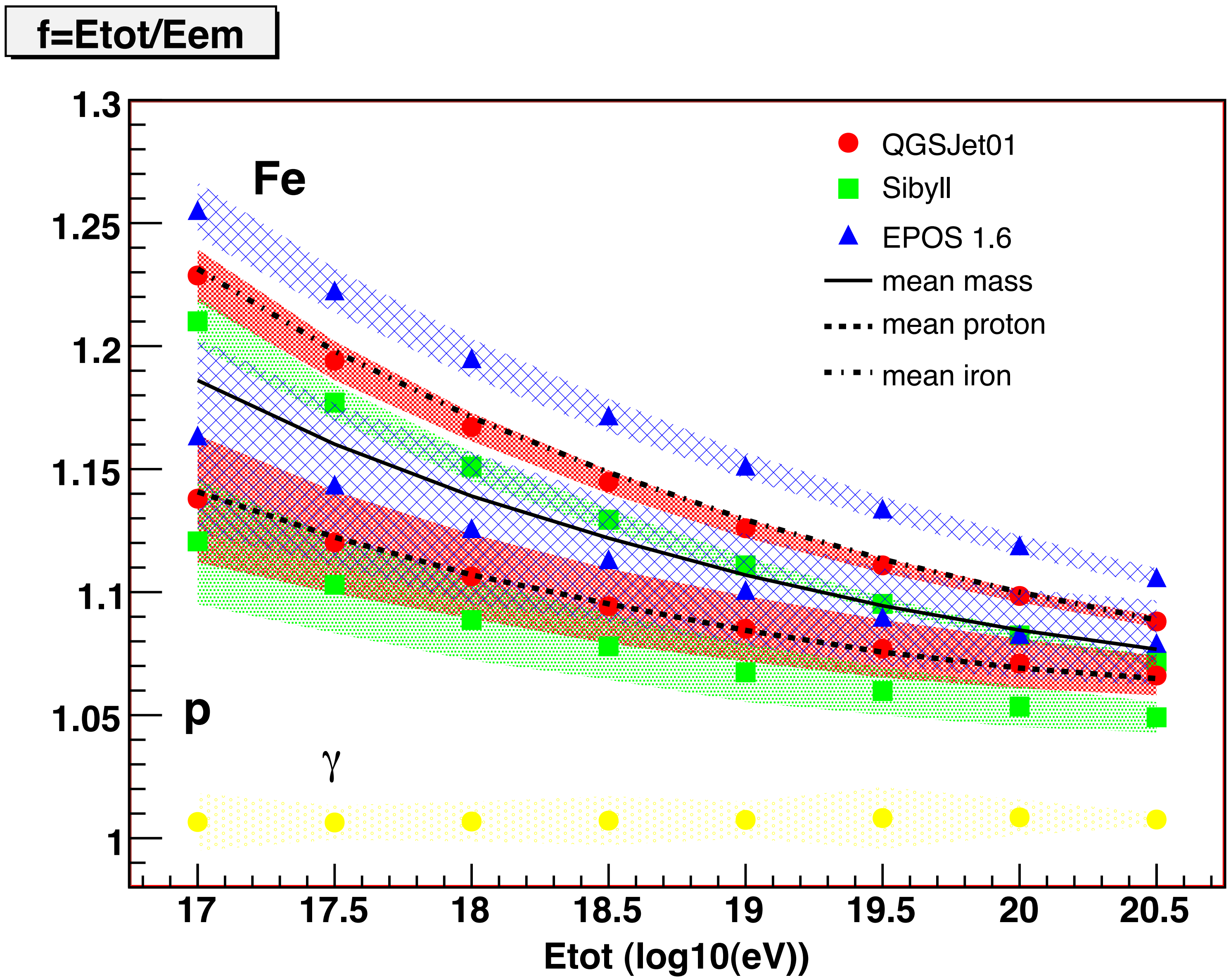


Fluorescence detector energy

$$E_{\rm prim} = f_{\rm corr} \cdot \int \frac{\mathrm{d}E_{\rm ion}}{\mathrm{d}X}\, \mathrm{d}X$$

(Fluorescence yield uncertainty)

Systematic uncertainties of energy assignment

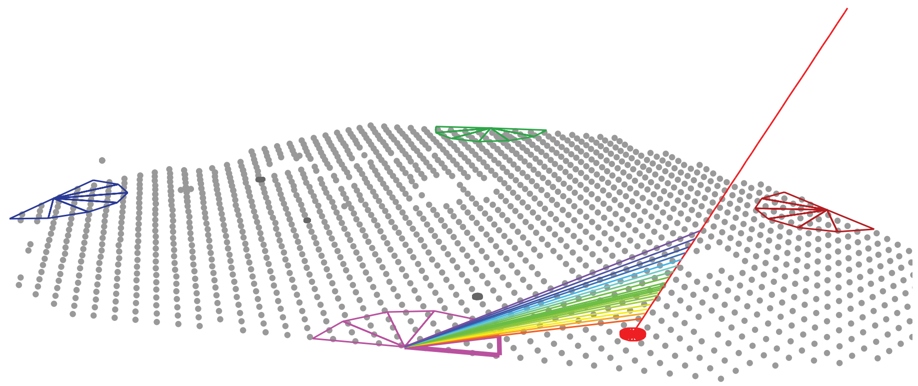


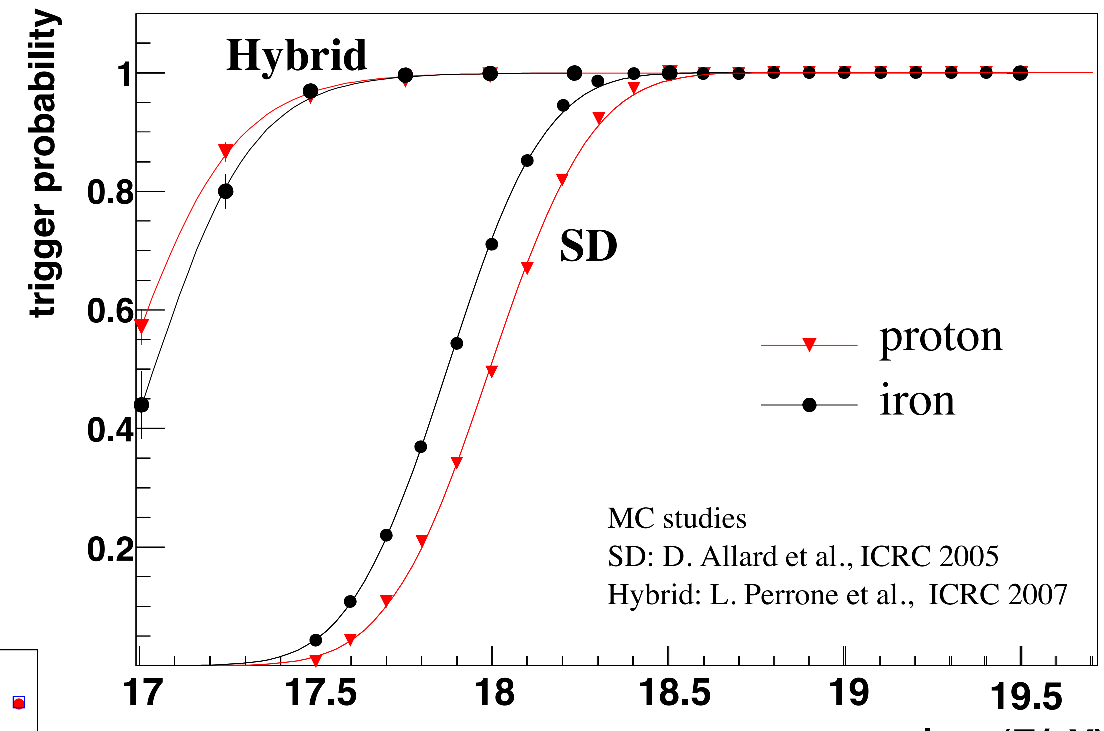
(T. Pierog et al., ICRC 2007)

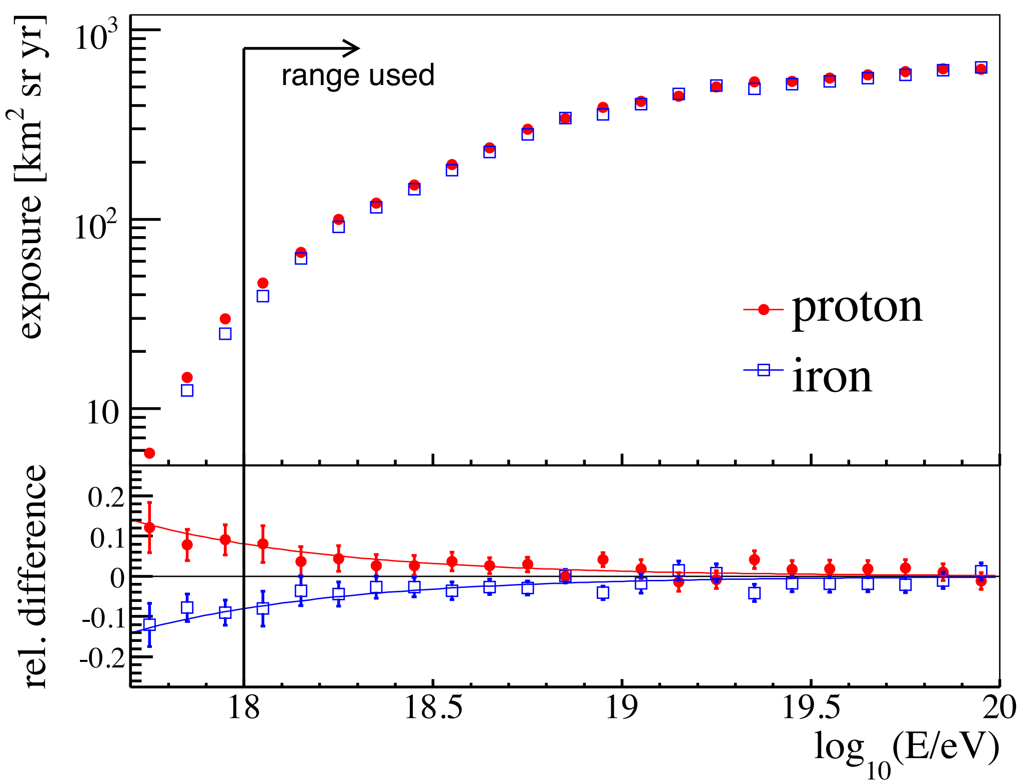
Model dependence of energy correction small

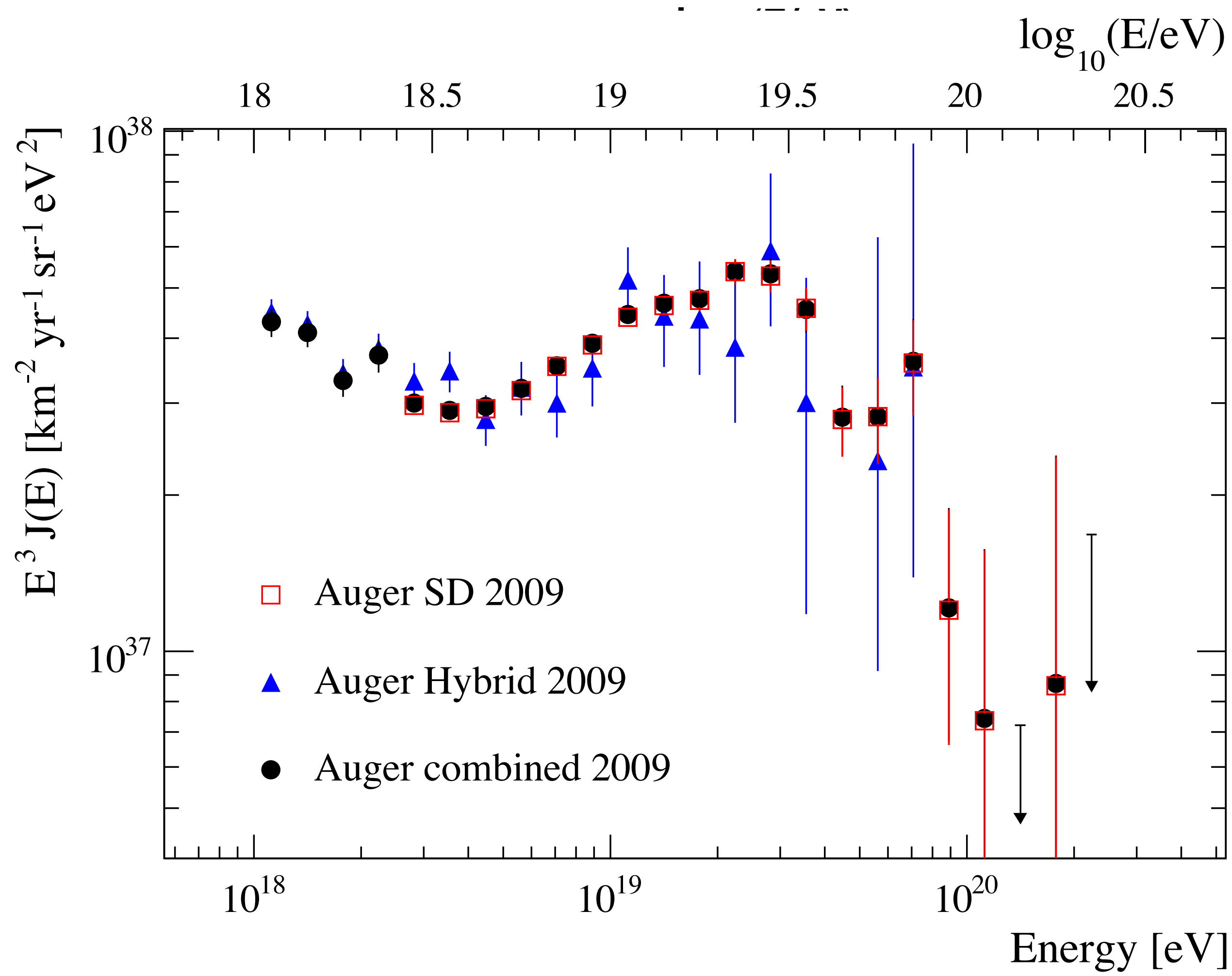
fluorescence yield	14%
telescope calibration	10%
reconstruction	10%
aerosols	5%
humidity	5%
overall	22%

Energy spectrum (surface array and hybrid events)



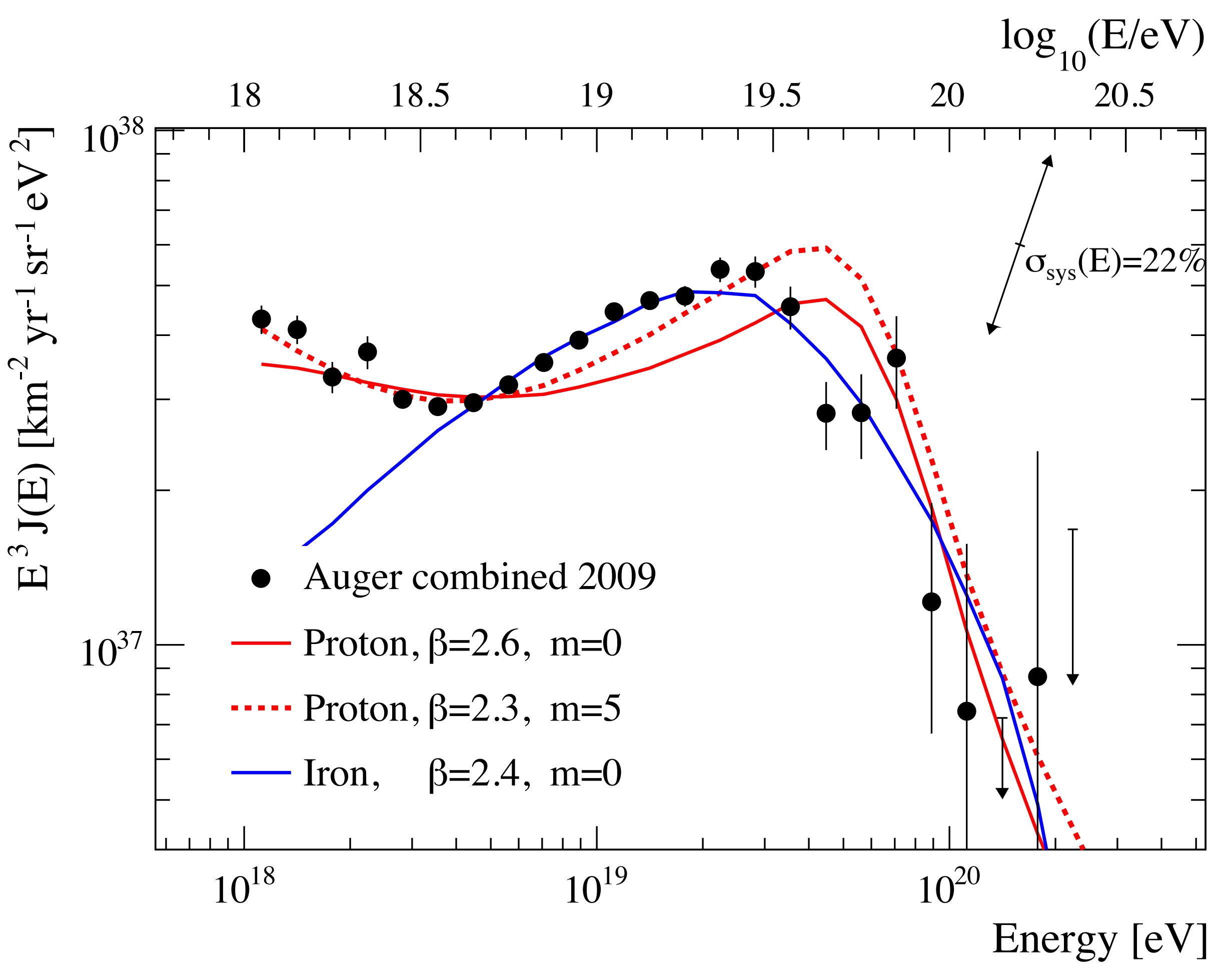






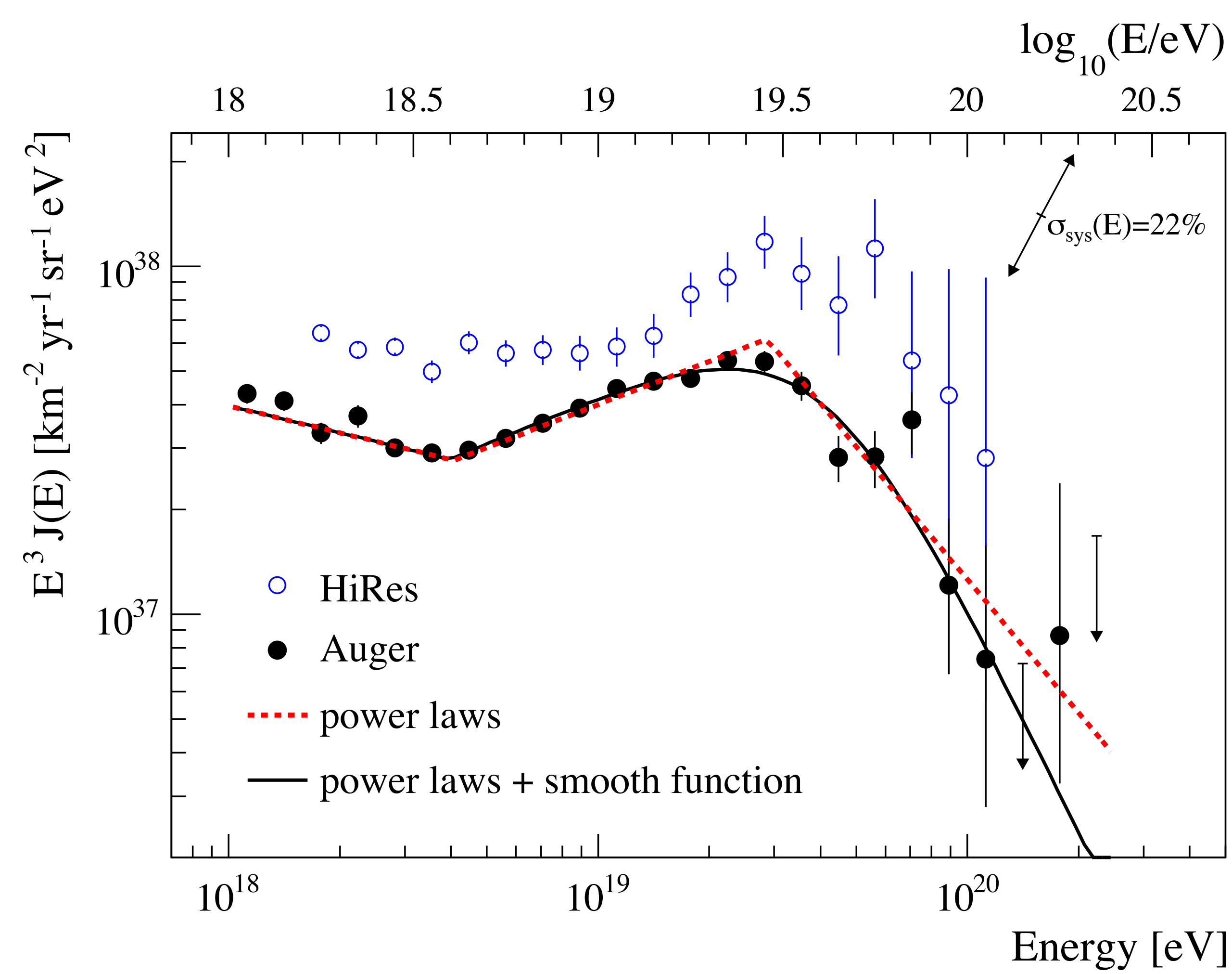
Exposure dependent on primary mass at low energy

Some comparisons ...



HiRes Stereo spectrum

- 1997 – 2006
- ε = 8300 km^2 sr yr



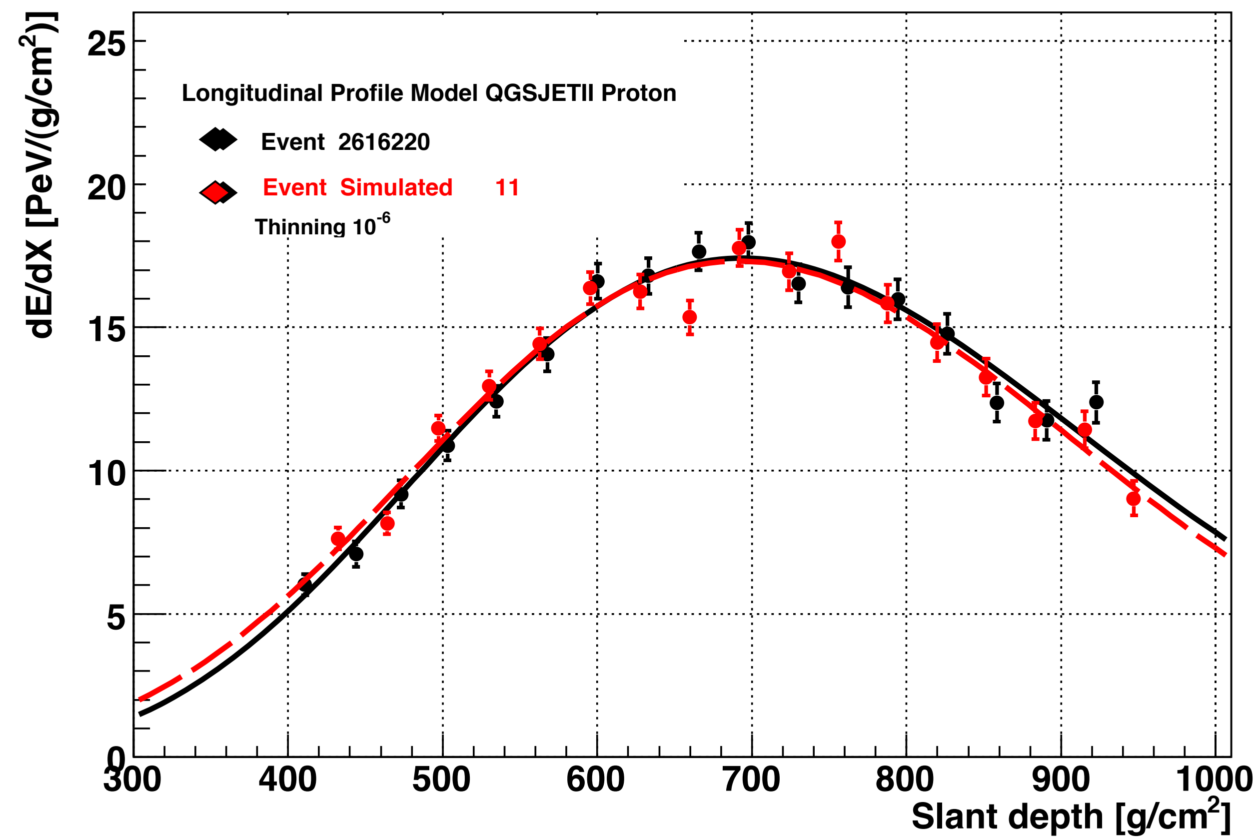
Auger Surface detector spectrum

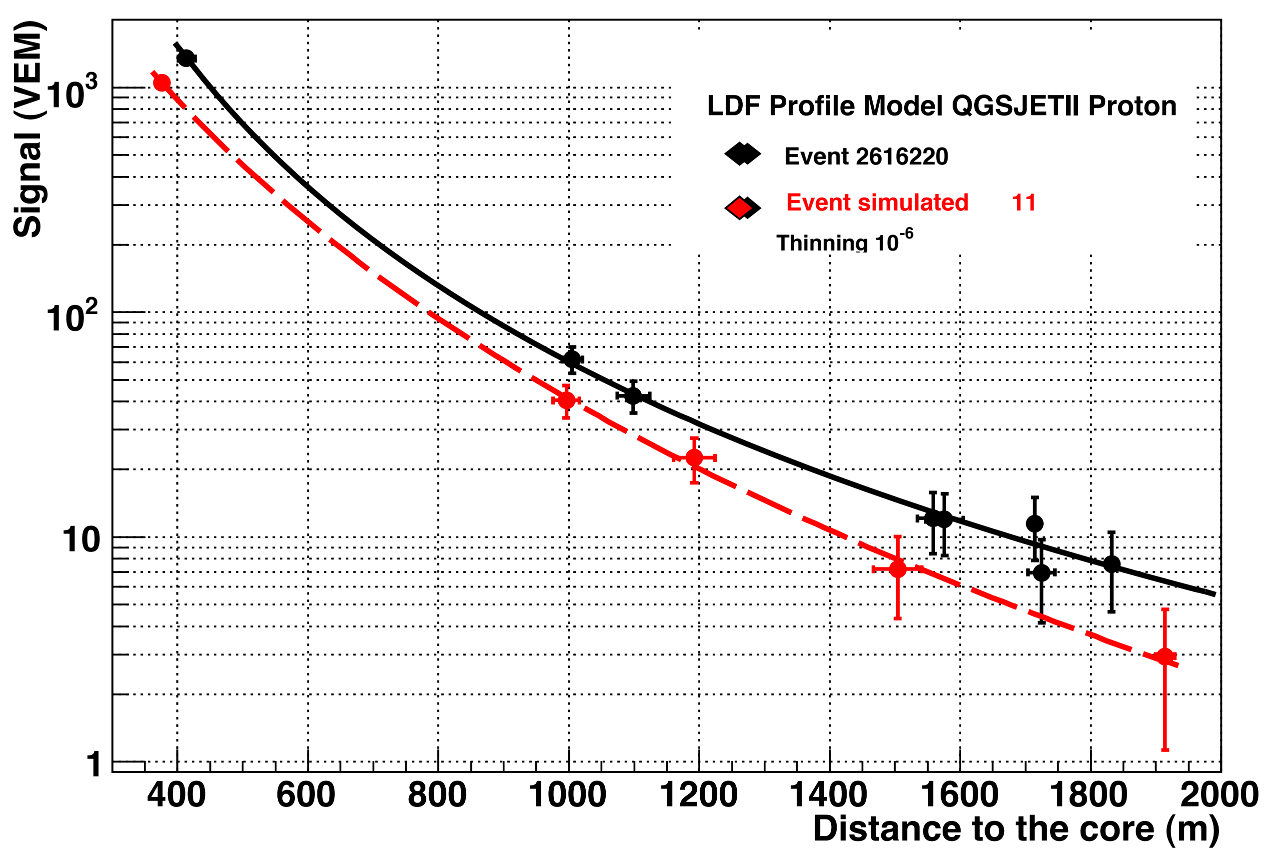
- 01/2004 - 12/2008
- $\mathcal{E} = 12.790\ \mathrm{km}^2\ \mathrm{sr\ yr}$
- $\approx$ 2 years of full Auger
- $>$ 35000 events

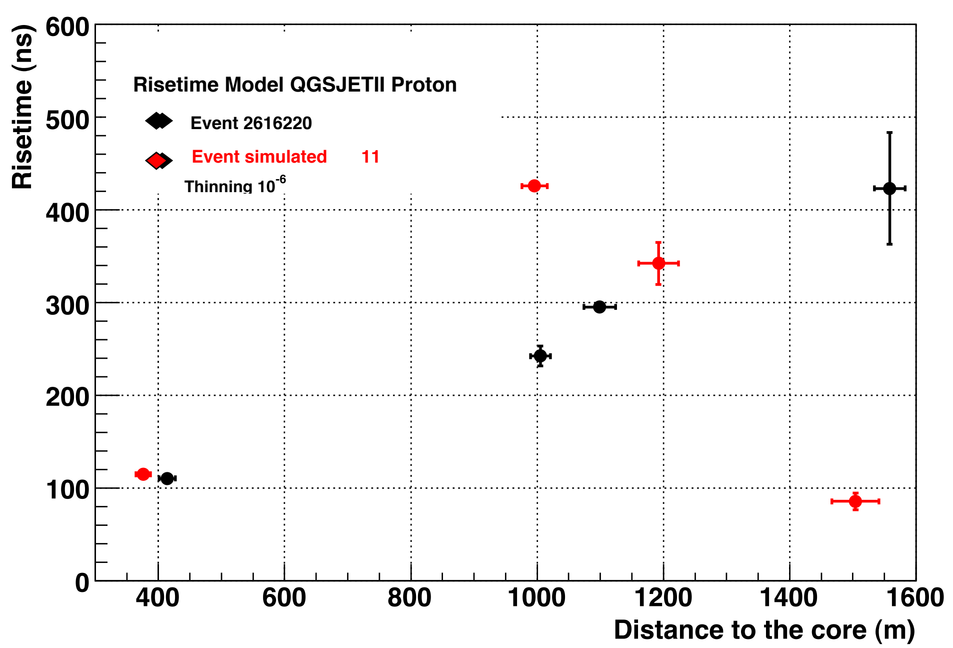
Simulations fail to describe events (i)

QGSJET II proton hypothesis

Event 2616220
$\theta = 30°$, $E = 1.1\times10^{19}$ eV
iron-like event





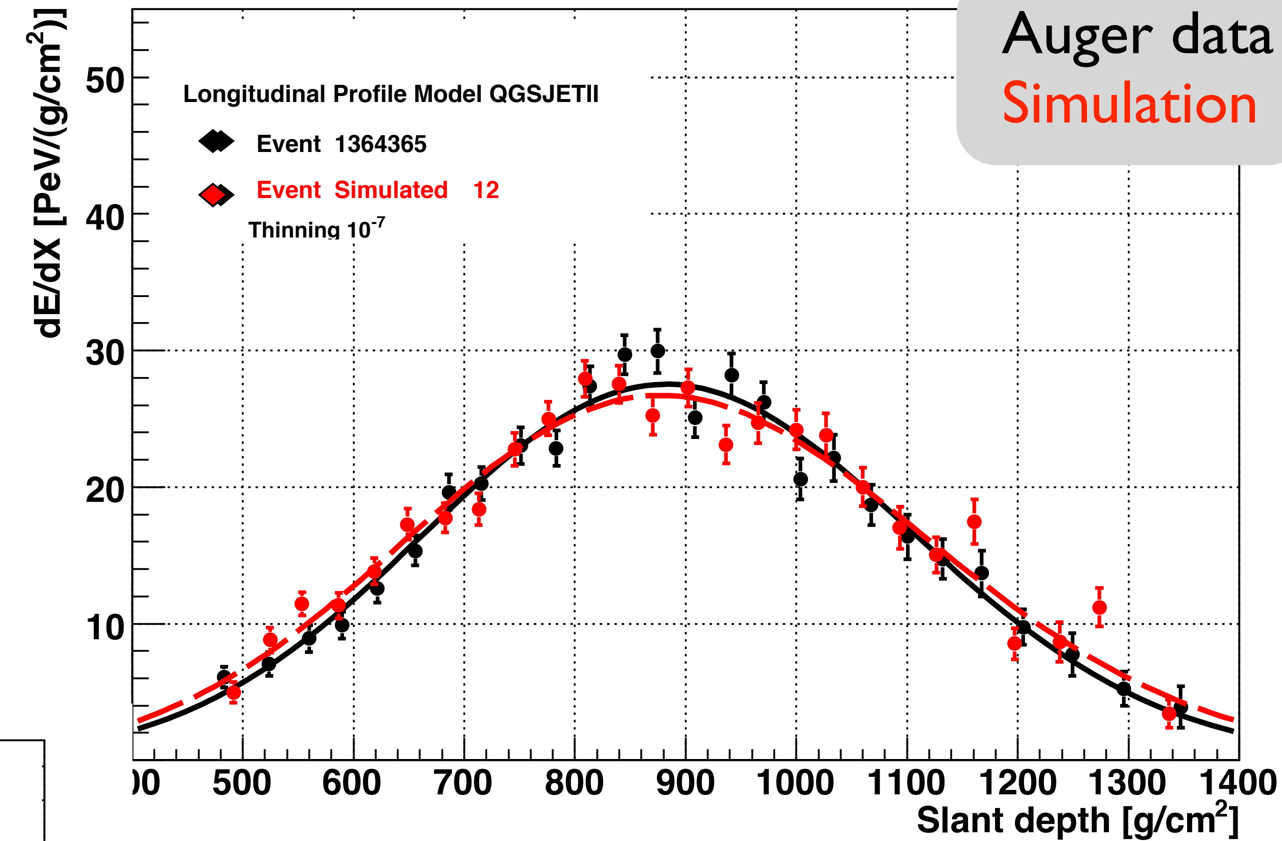


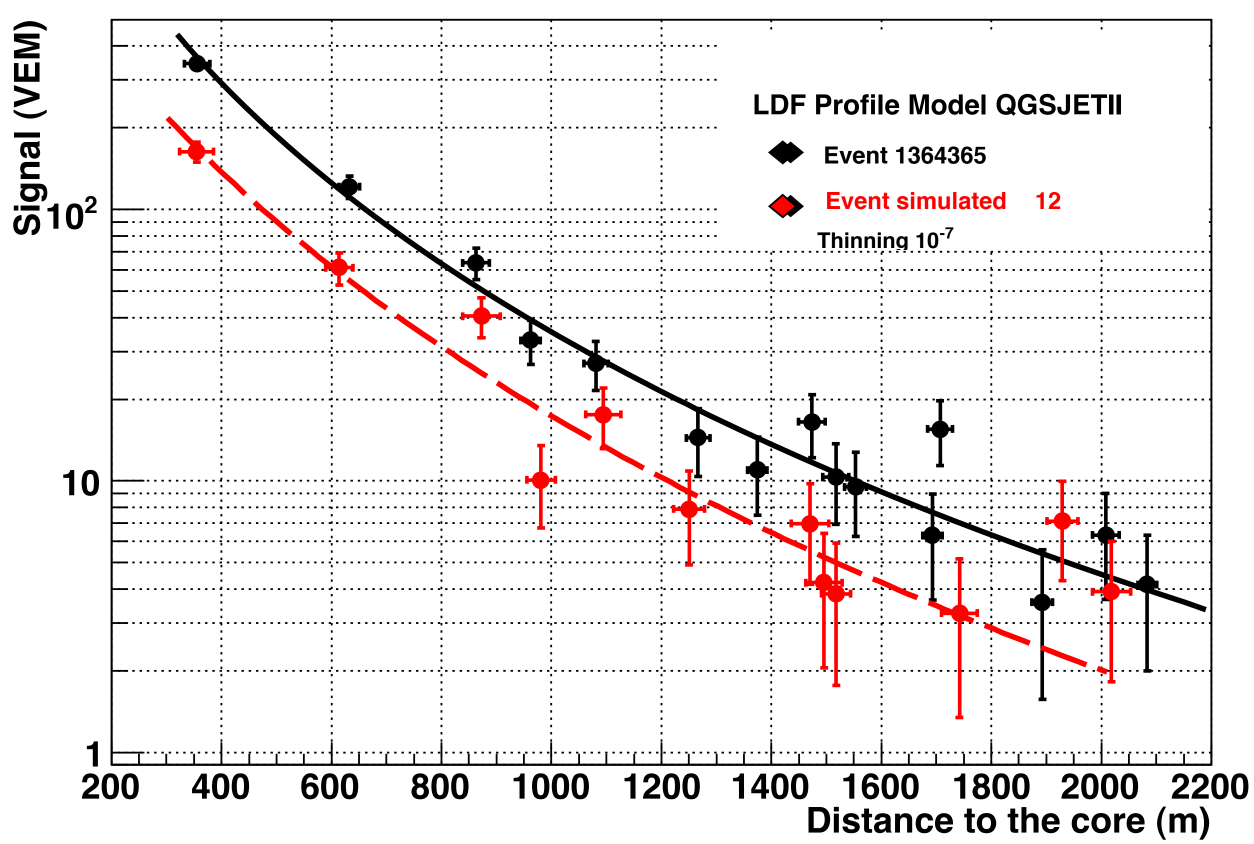
Simulations fail to describe events (ii)

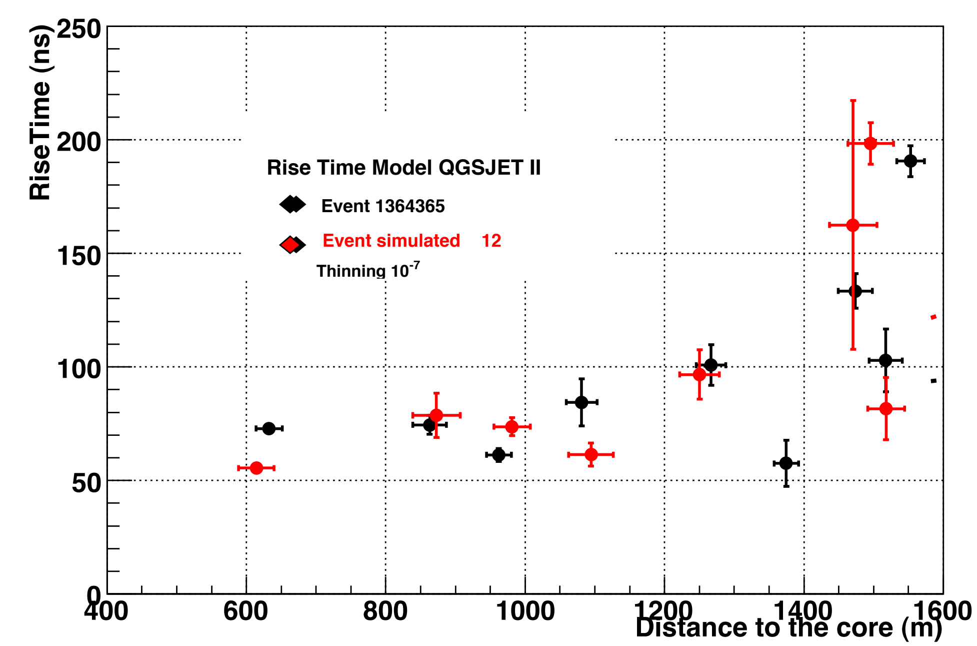
QGSJET II proton hypothesis

Event 1364365
$\theta = 64°$, $E = 1.7 \times 10^{19}$ eV
Xmax proton-like
muon dominated signal

Auger data
Simulation



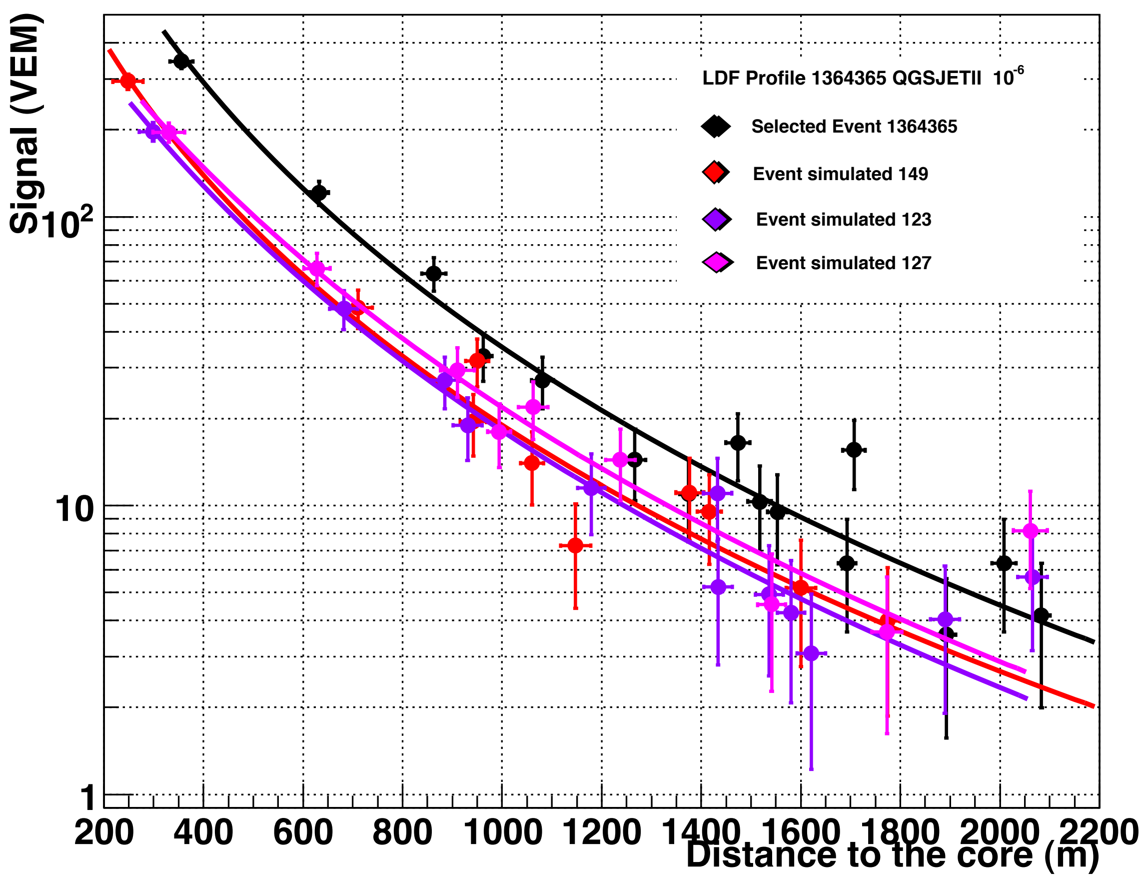


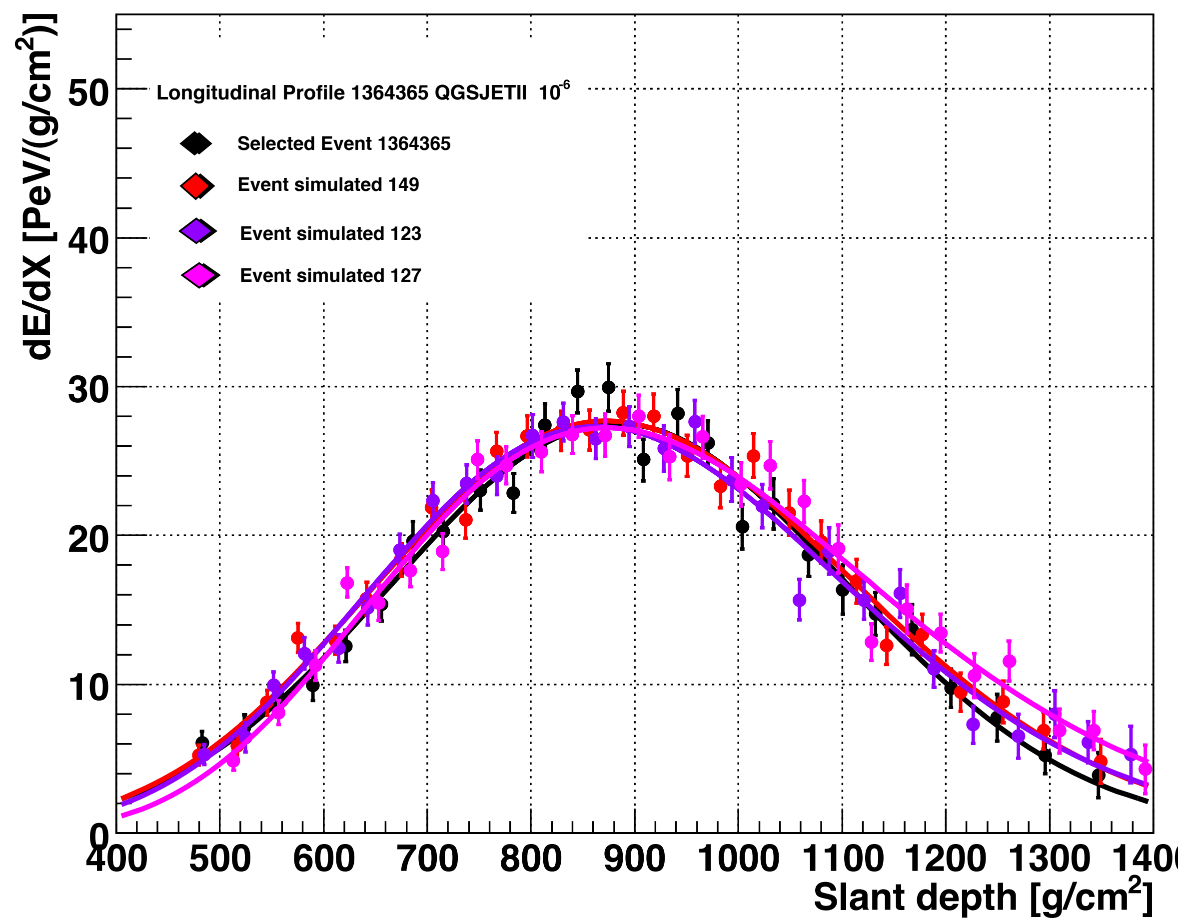


Shower-to-shower fluctuations

Different simulations with QGSJET II for same event

Event 1364365, θ = 64°, E = 1.7x10^{19} eV
Xmax proton-like, muon dominated signal



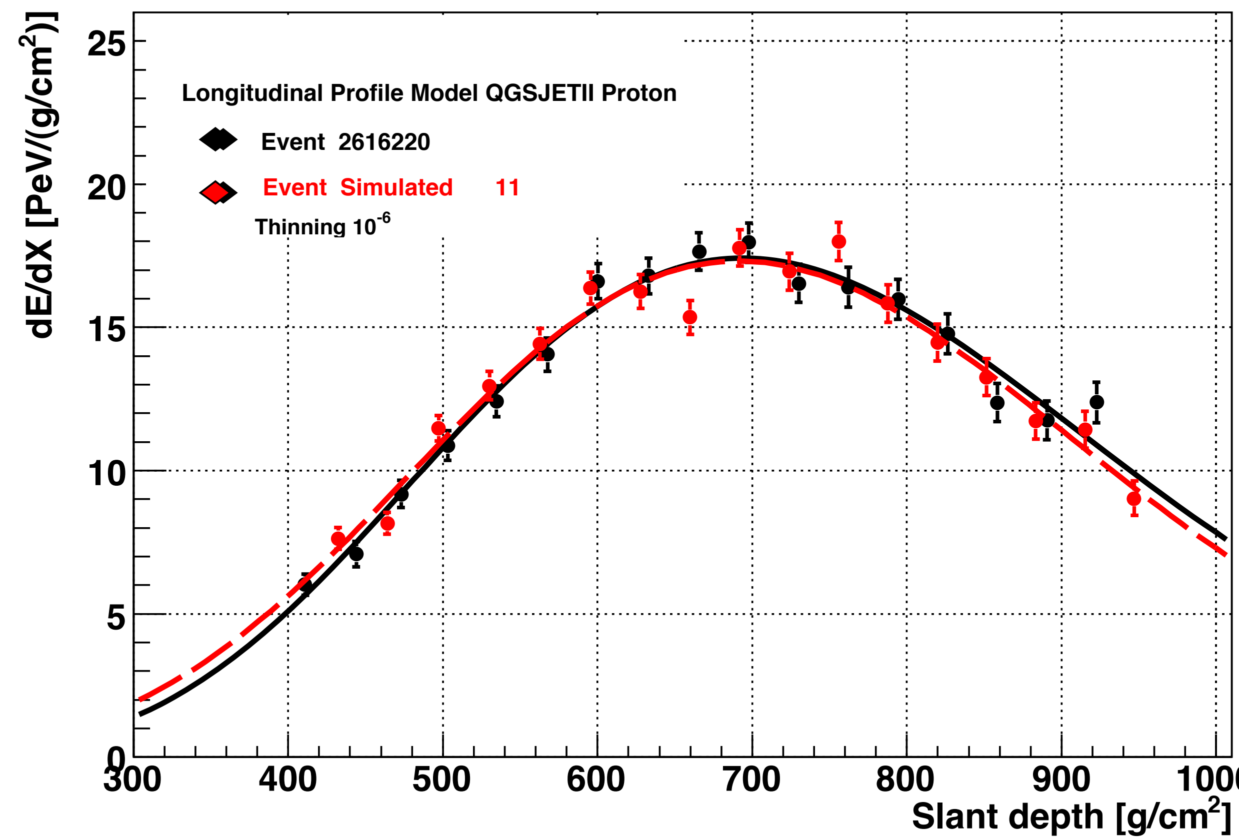


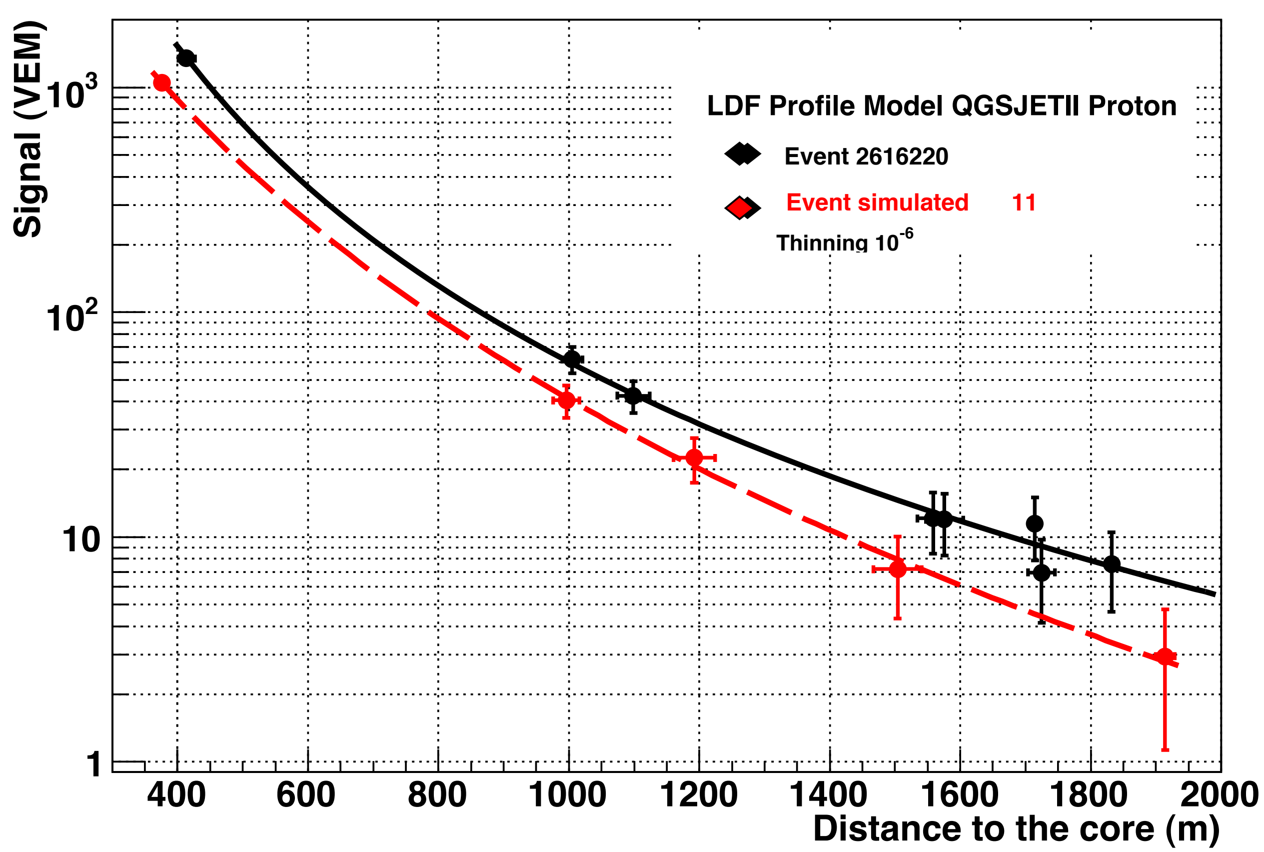
Fluctuations of SD signal smaller than 15%

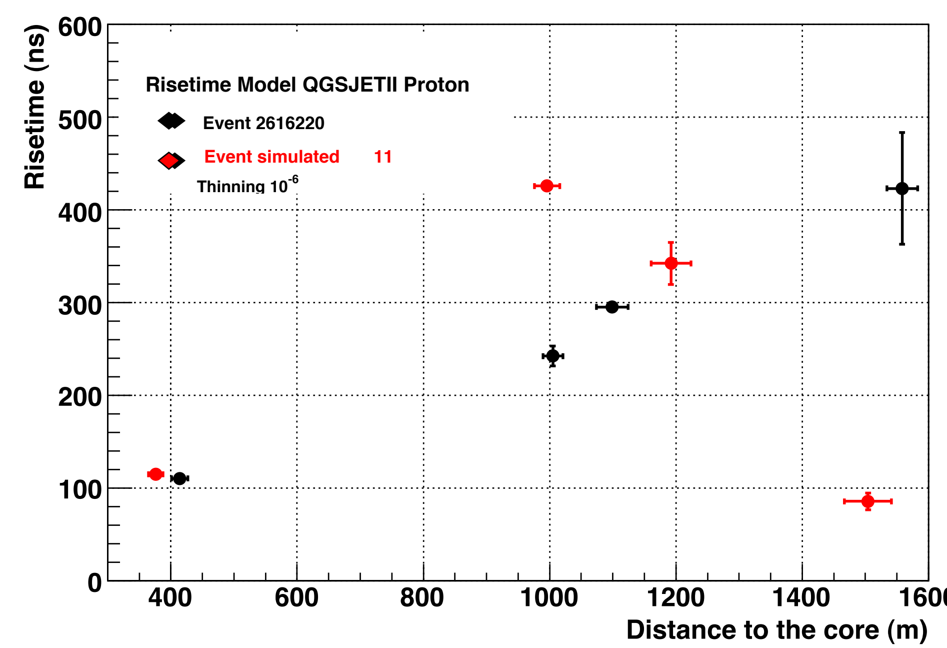
What about iron primaries ?

QGSJET II iron hypothesis

Event 2616220
θ = 30°, E = 1.1×10^{19} eV
iron-like event

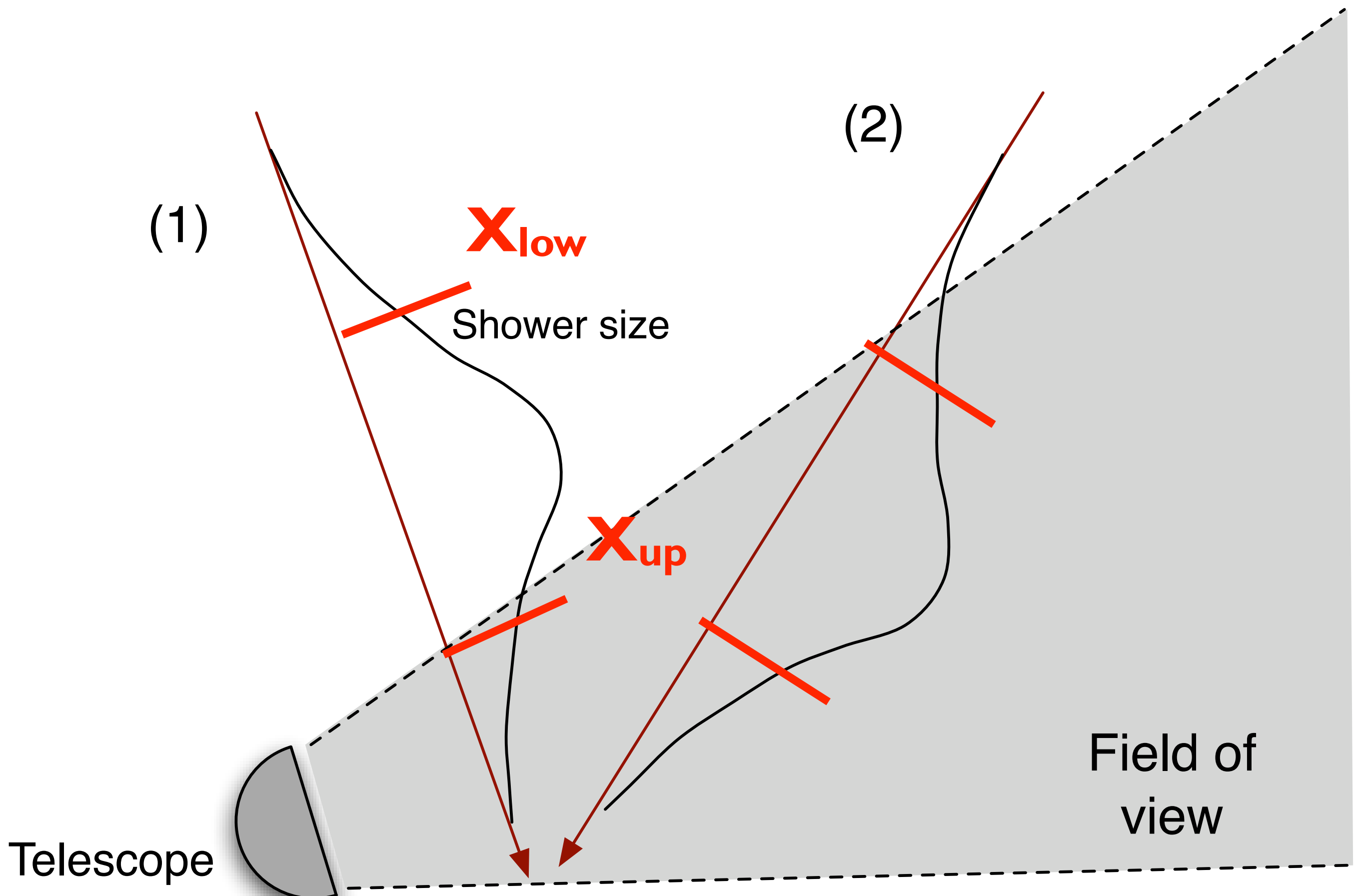




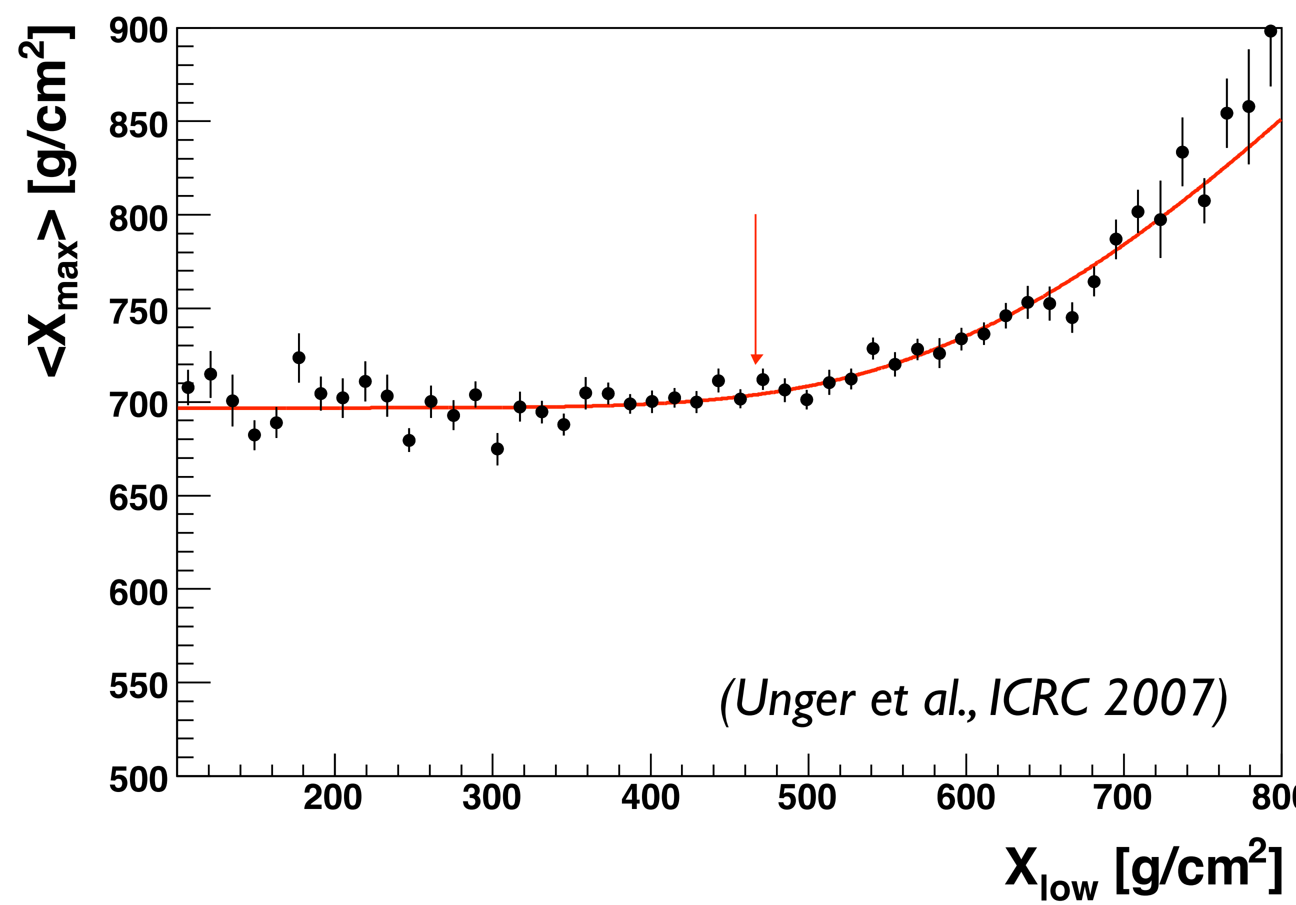


Mass composition

Composition: measurement of longitudinal profile

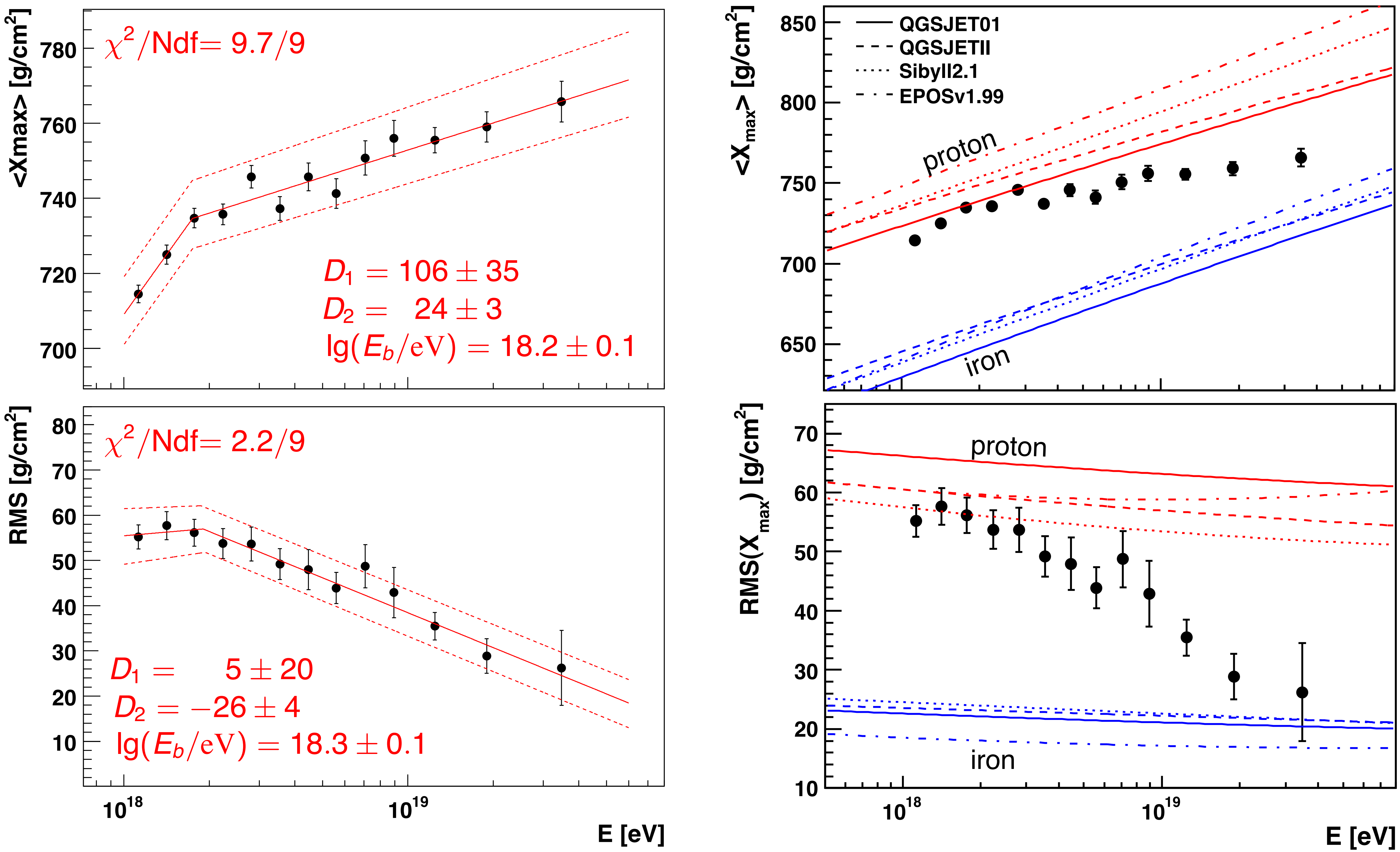


Field of view bias needs to be accounted for



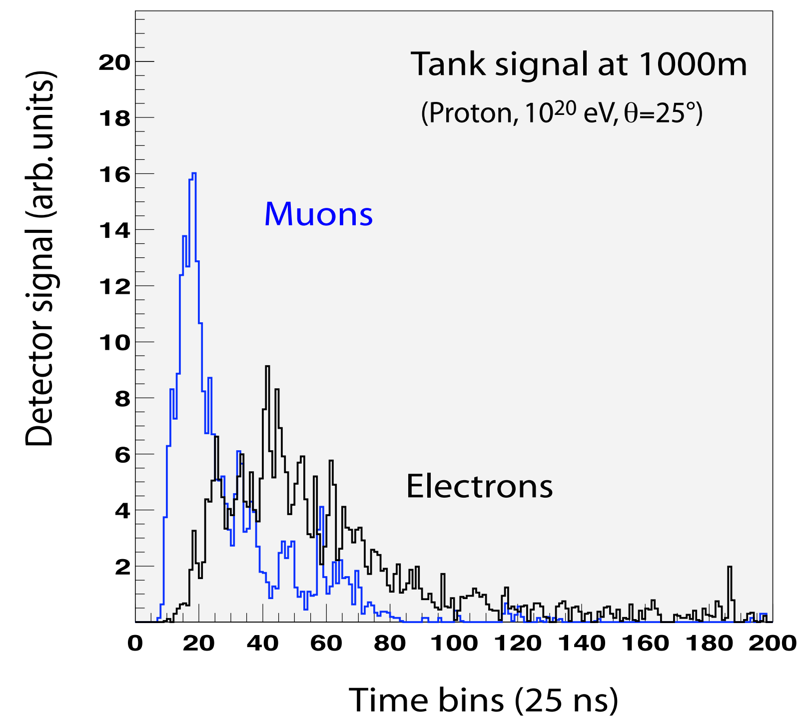
X_{low}, X_{up} are determined form data, no simulation needed

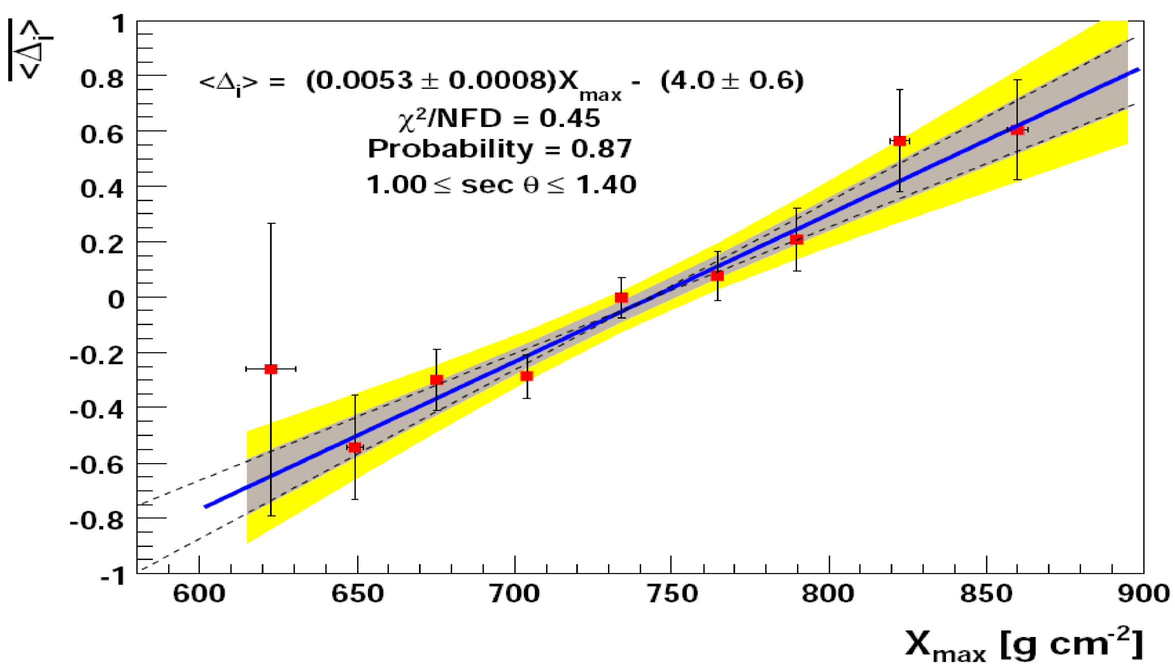
Xmax measurement and composition

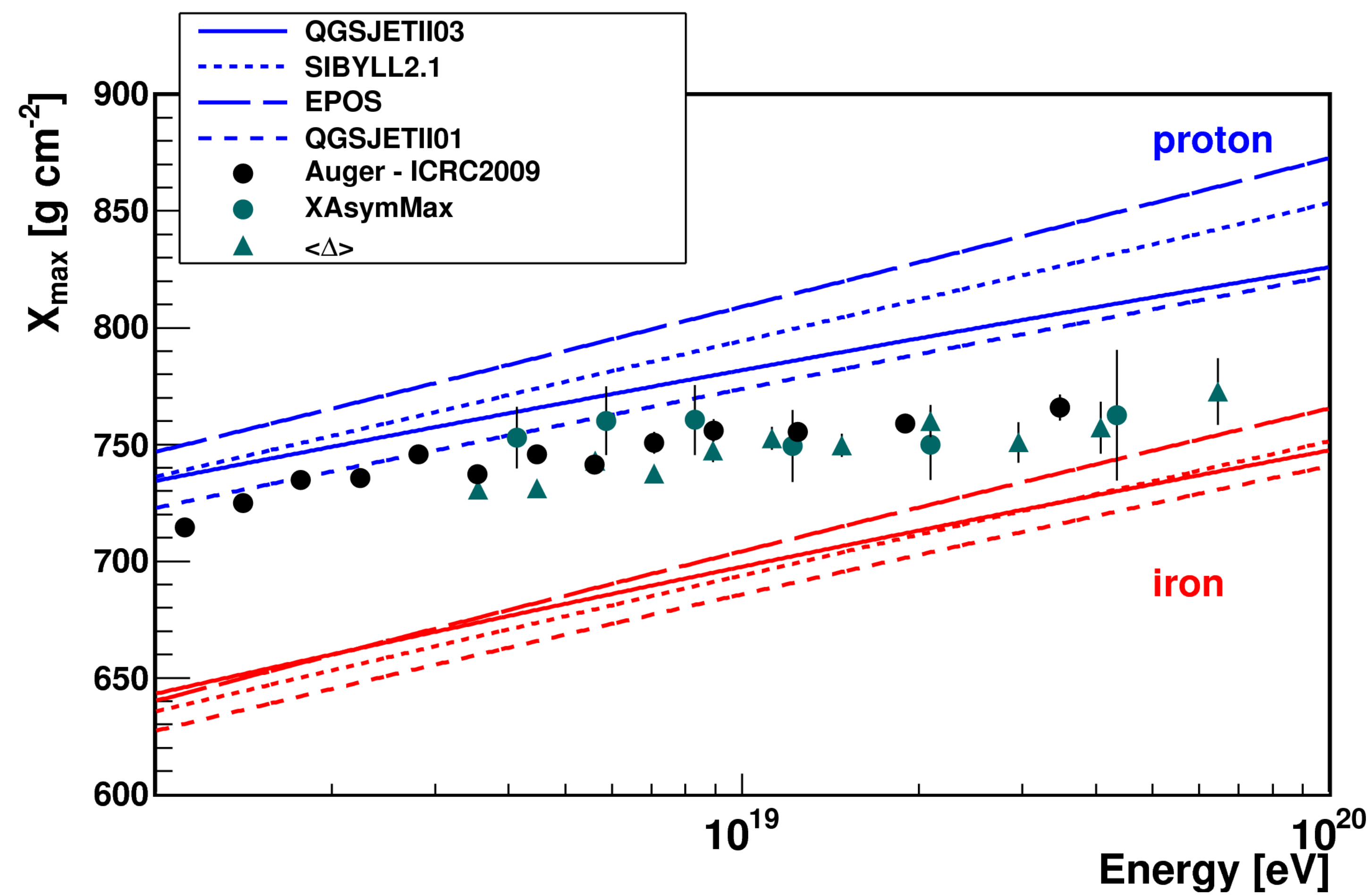


Other composition-sensitive variables

Other composition sensitive variables:
rise time, asymmetries, curvature







Problem:
Cannot trust Monte Carlo predictions, need mapping of these observables to X_{max} (large fluctuations)

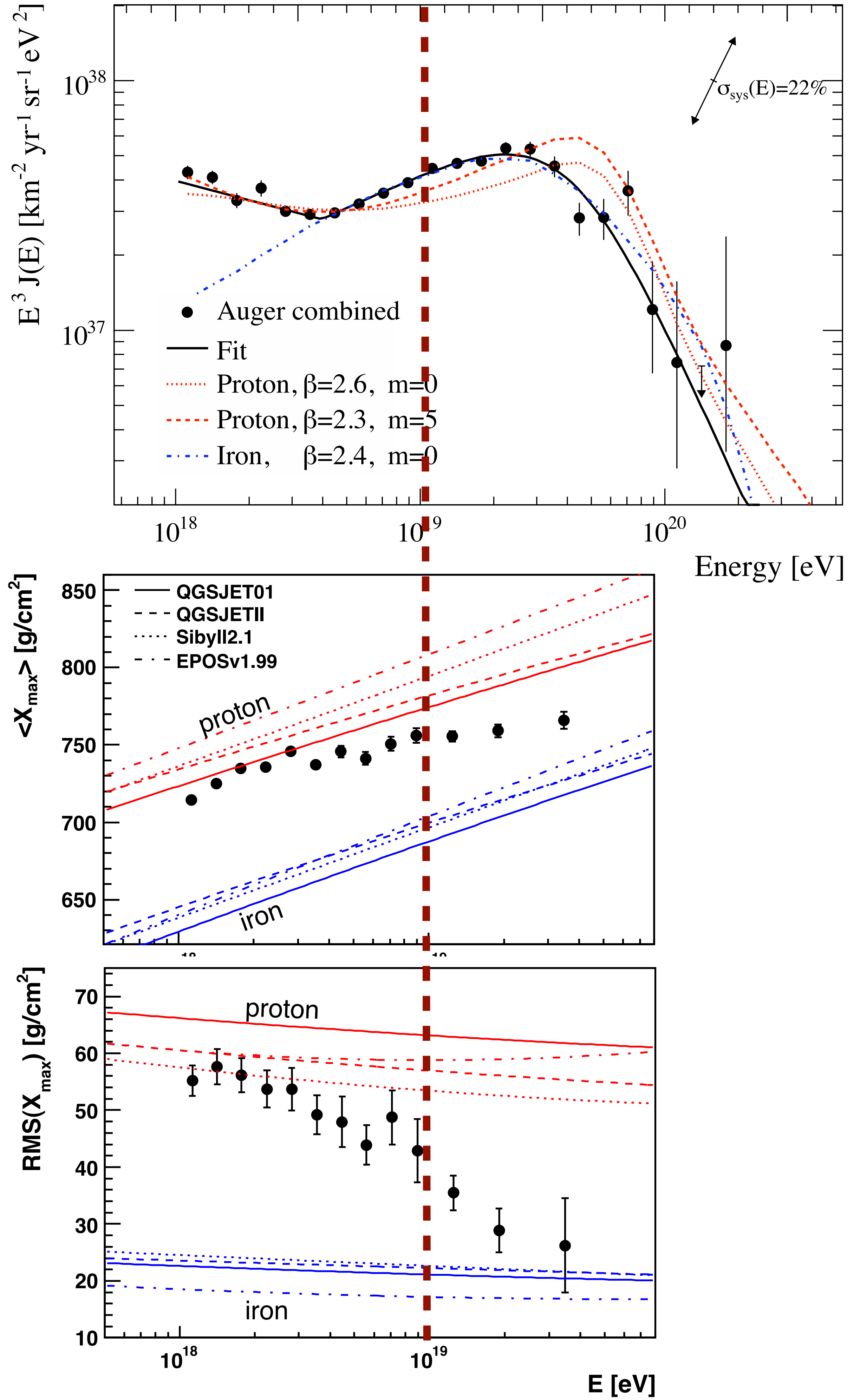
Interaction model analysis

Universality method
- em. component universal
- muonic contribution: part of signal

Time trace analysis
- jump method (muon counting)
- smoothing method (em. component)

Simulation of individual hybrid events

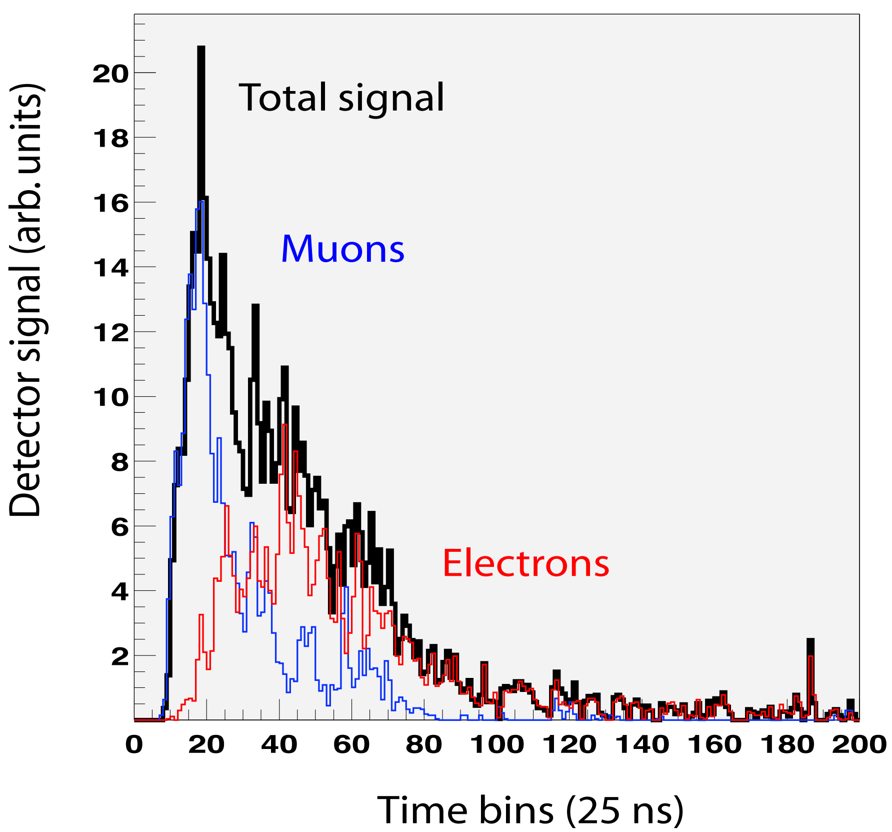
Analysis of data at about 10^{19} eV
QGSJET II, protons as reference scale

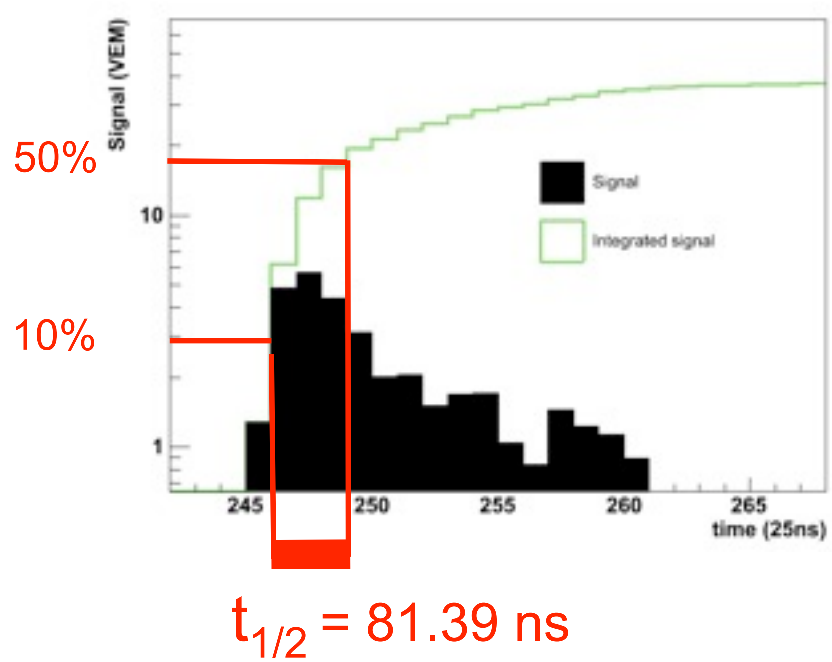


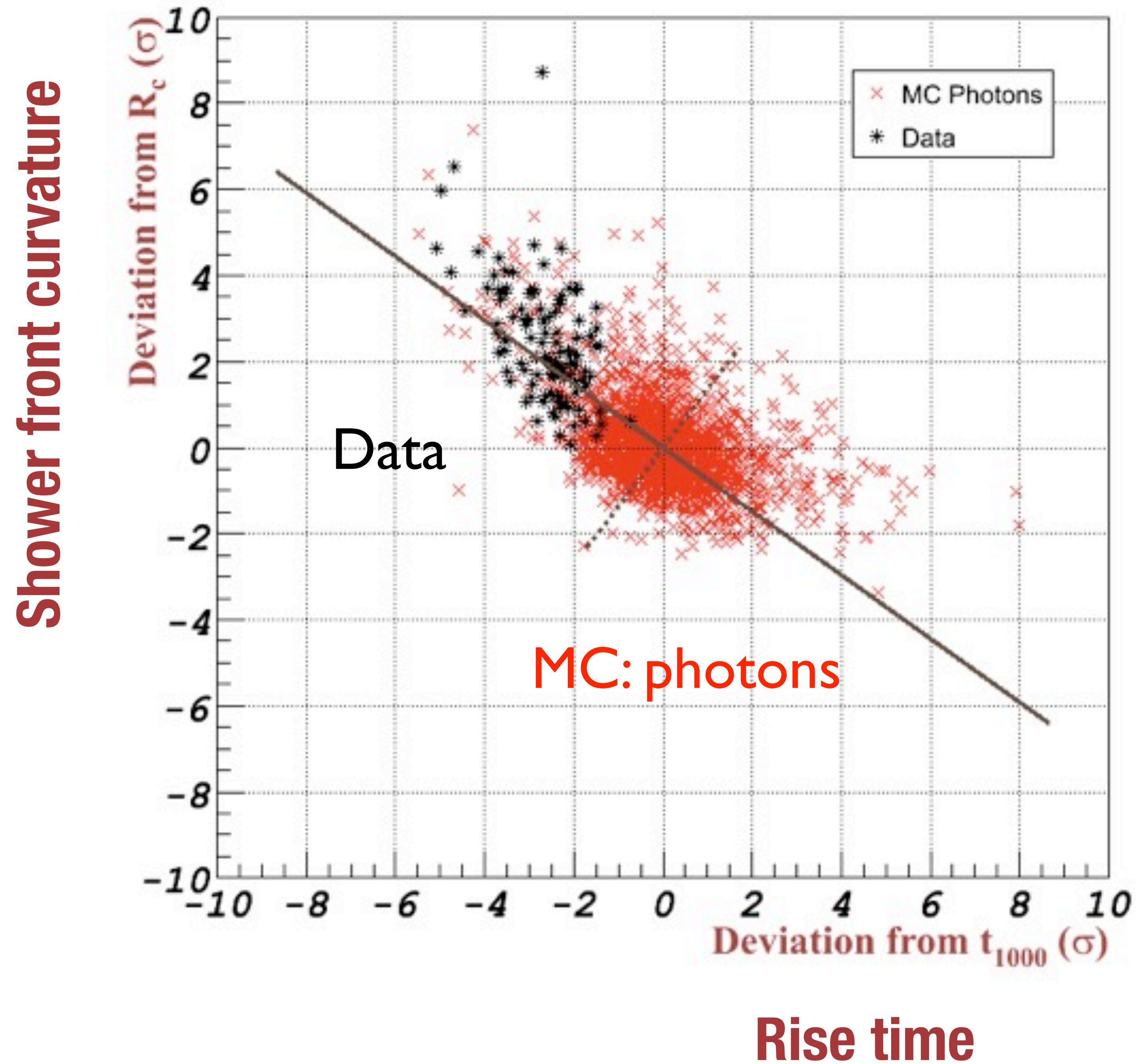
Photon and neutrino limits

Photon limit (fluorescence and surface array data)

Signal rise time

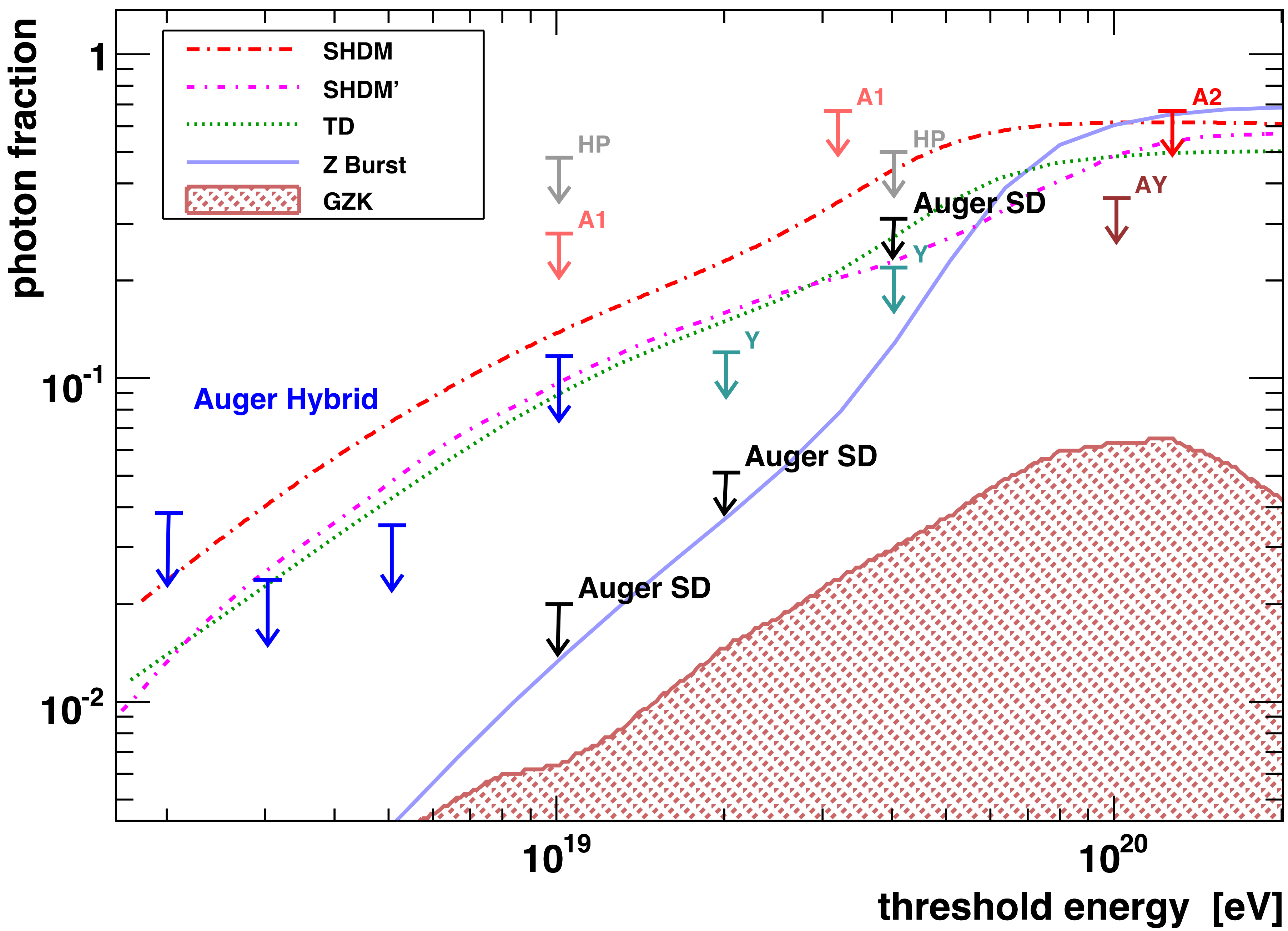






Only dependent on simulation of photon showers

Compilation of integral photon limits



Auger Hybrid:
Auger Collaboration '09

Auger SD:
Auger Collaboration '08

HP: Ave et al. '00 & '02
A1: Shinozaki et al. '02
A2: Risse et al. '05
AY: Rubtsov et al. '06
Y: Glushkov et al. '07

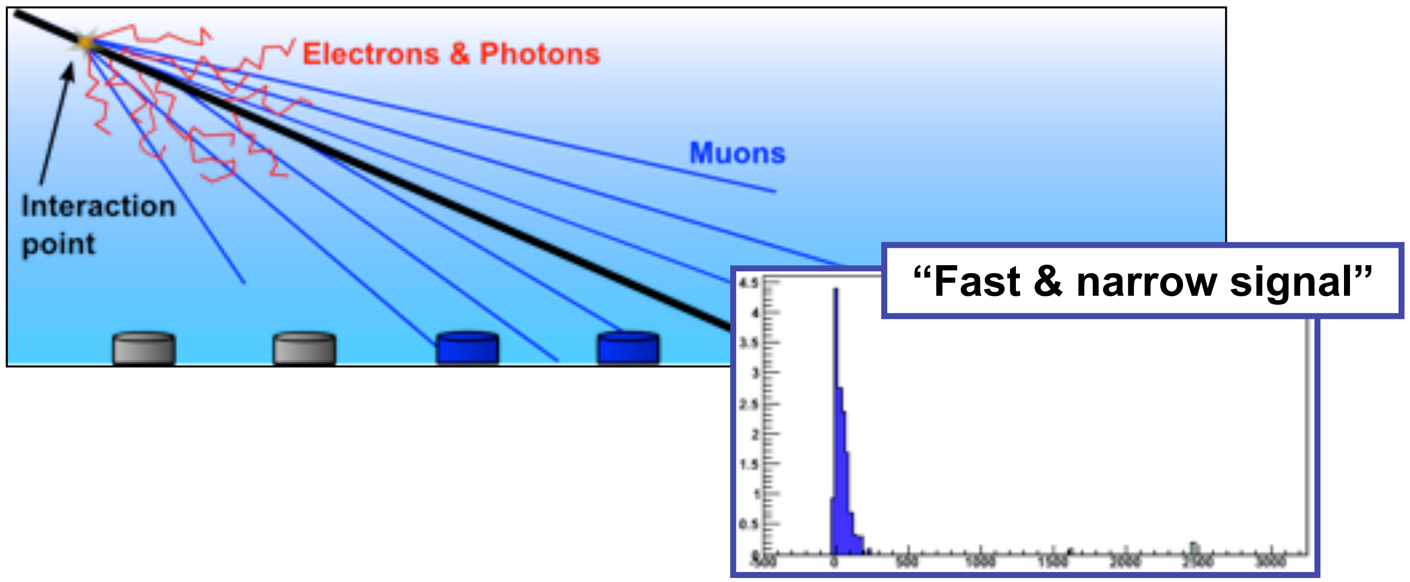
SHDM, TD, Z Burst:
Gelmini et al. '05

SHDM': Ellis et al. '06

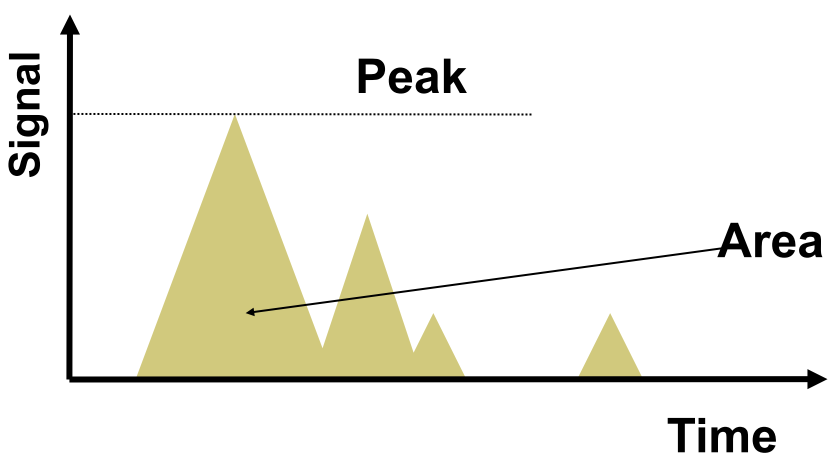
GZK: Gelmini et al. '07

Auger ICRC 2009

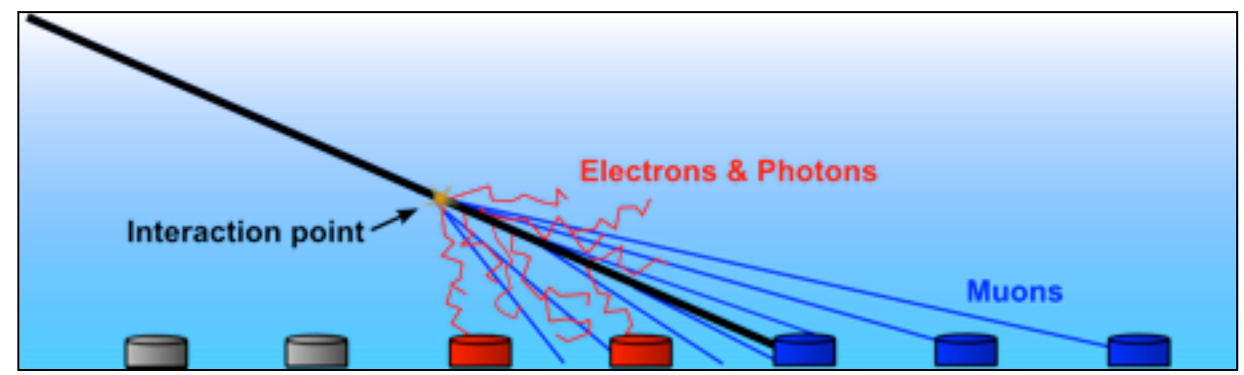
Neutrino searches

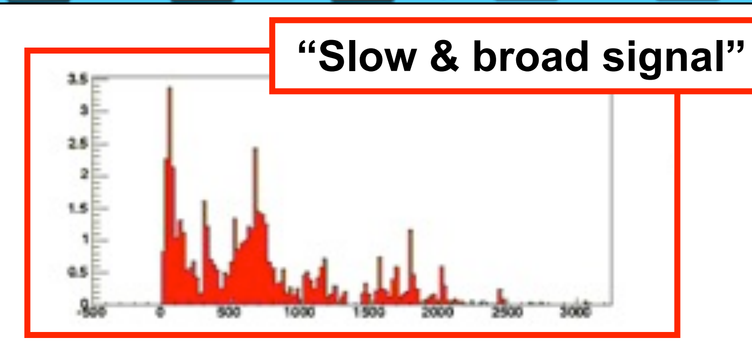


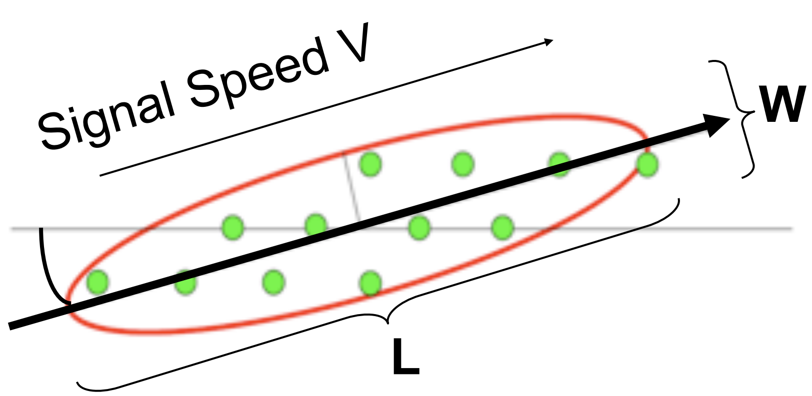
Observables to search for deep and young showers



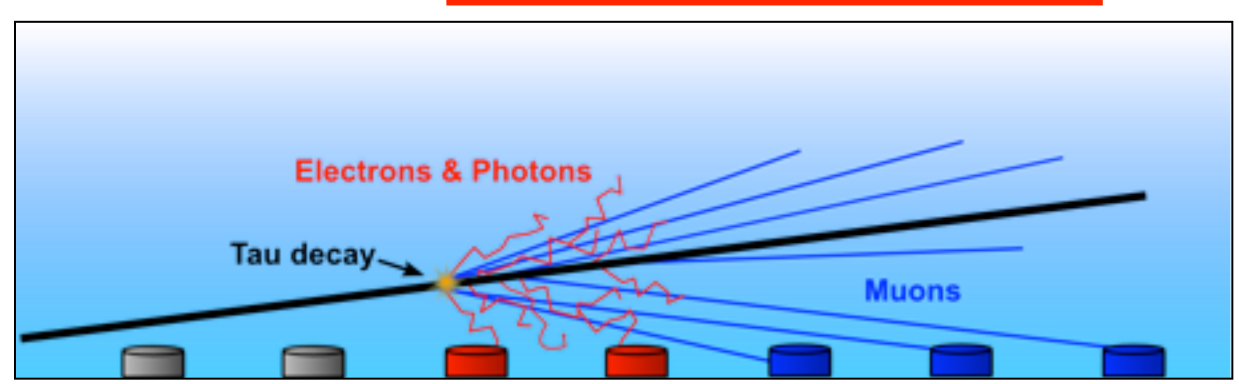
Ratio area over peak



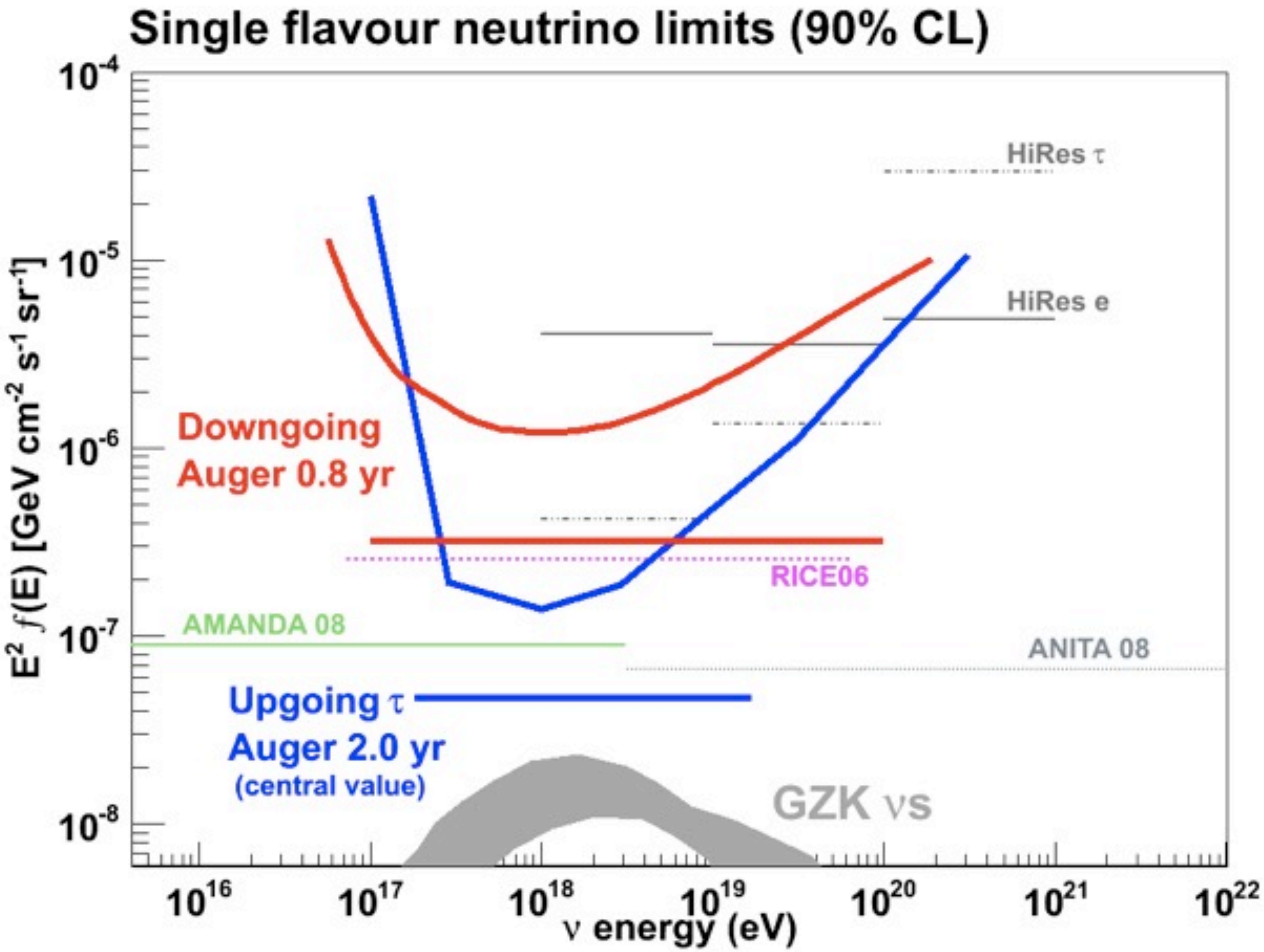




Apparent signal speed



Compilation of differential and integral limits

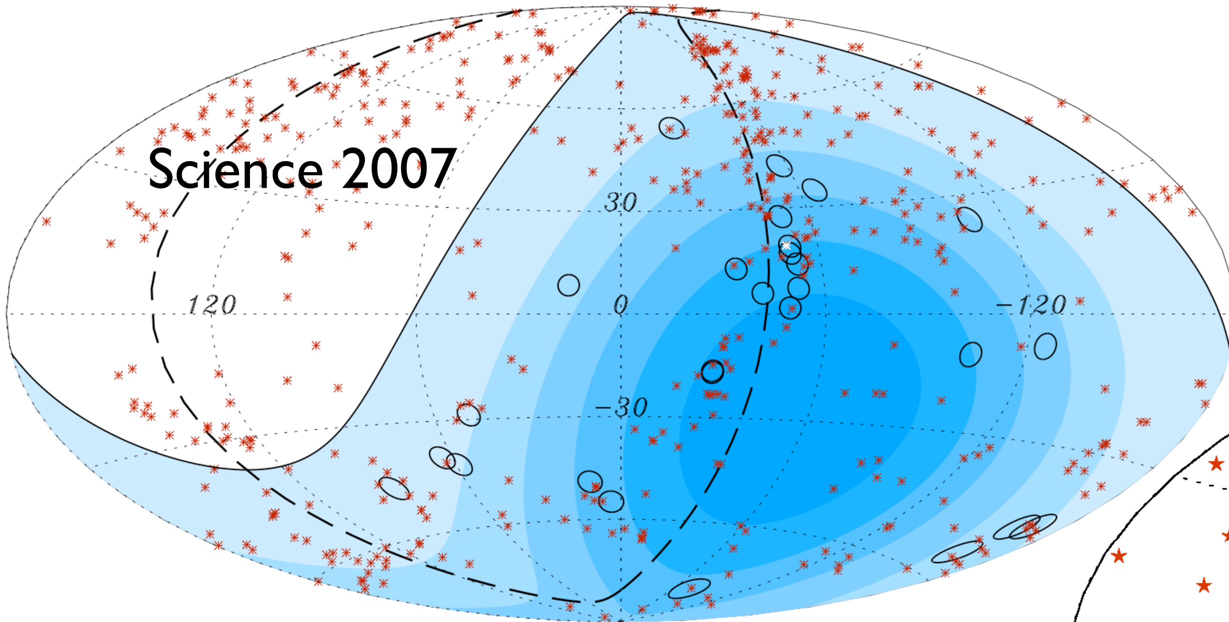


Auger ICRC 2009

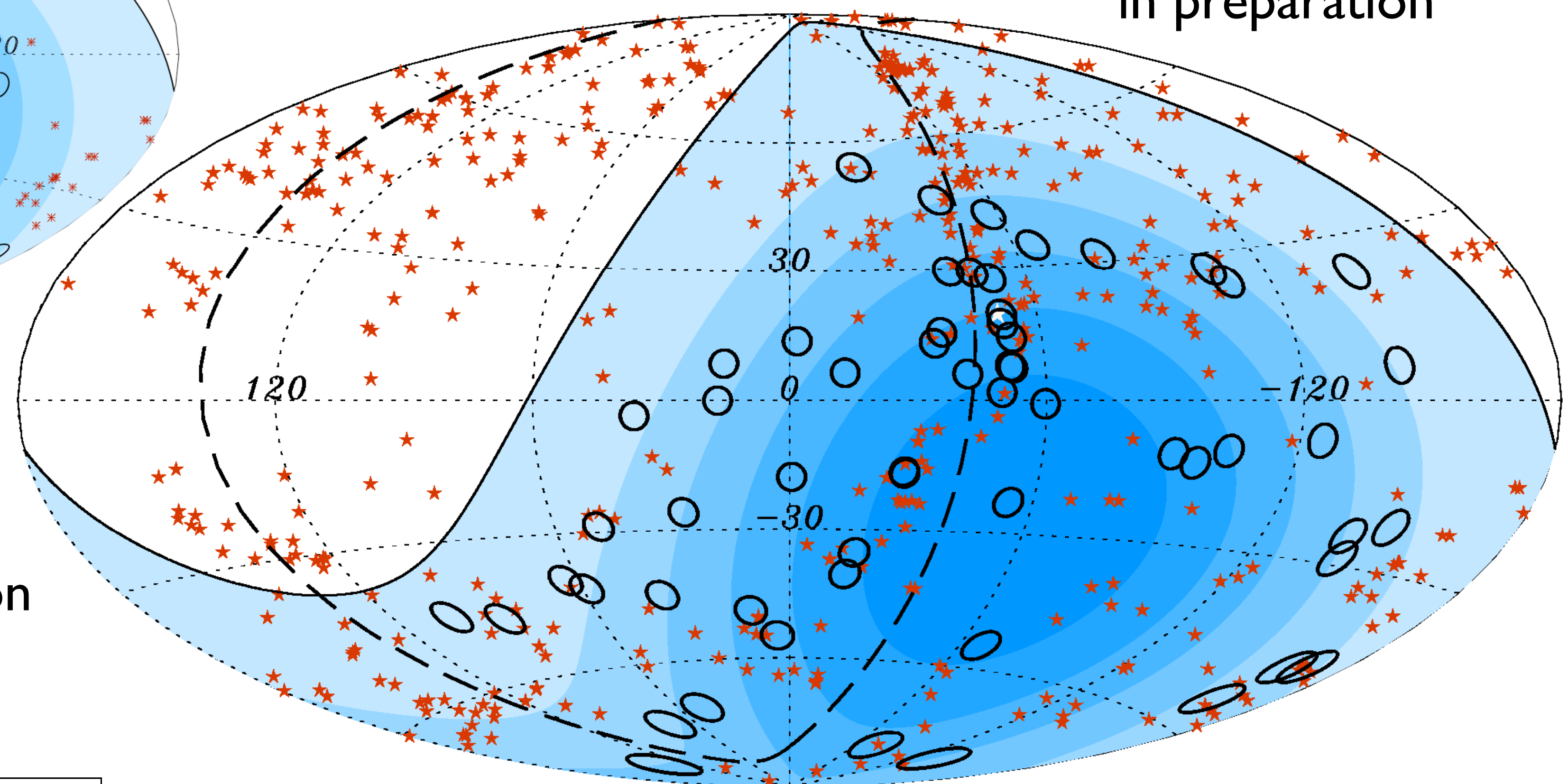
AUGER limits	Down 01Nov07-29Feb09	Up 01Jan04-29Feb09
K [GeV cm^{-2} s^{-1} sr^{-1}]	3.2×10^{-7}	4.7×10^{-8}

Arrival direction distribution

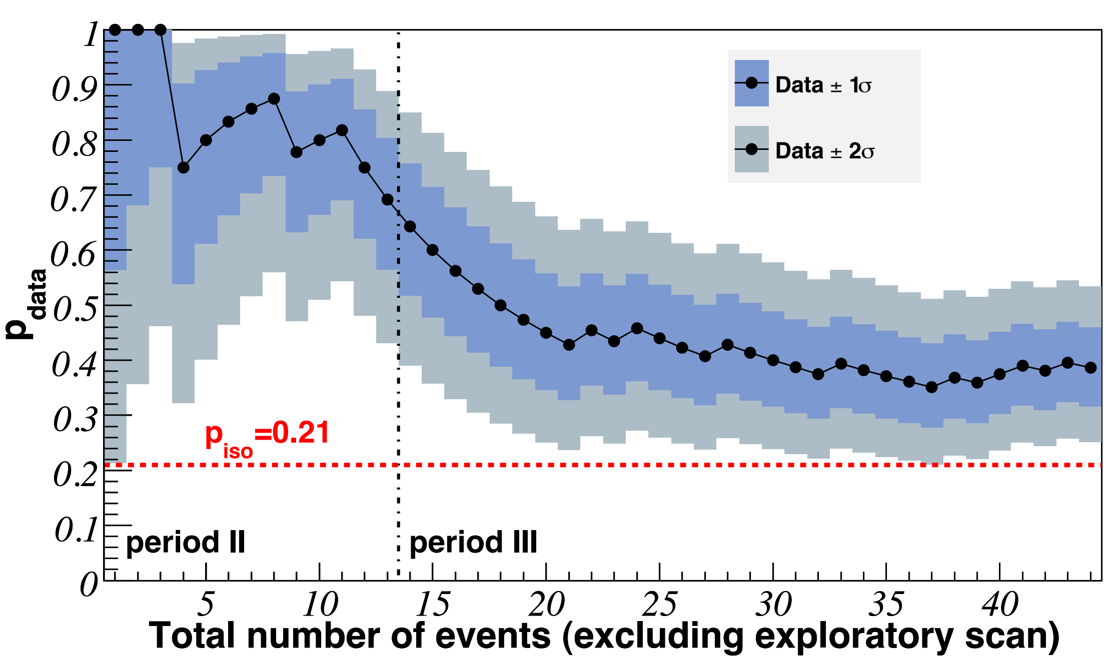
Update of AGN correlation



Astropart. Phys., in preparation

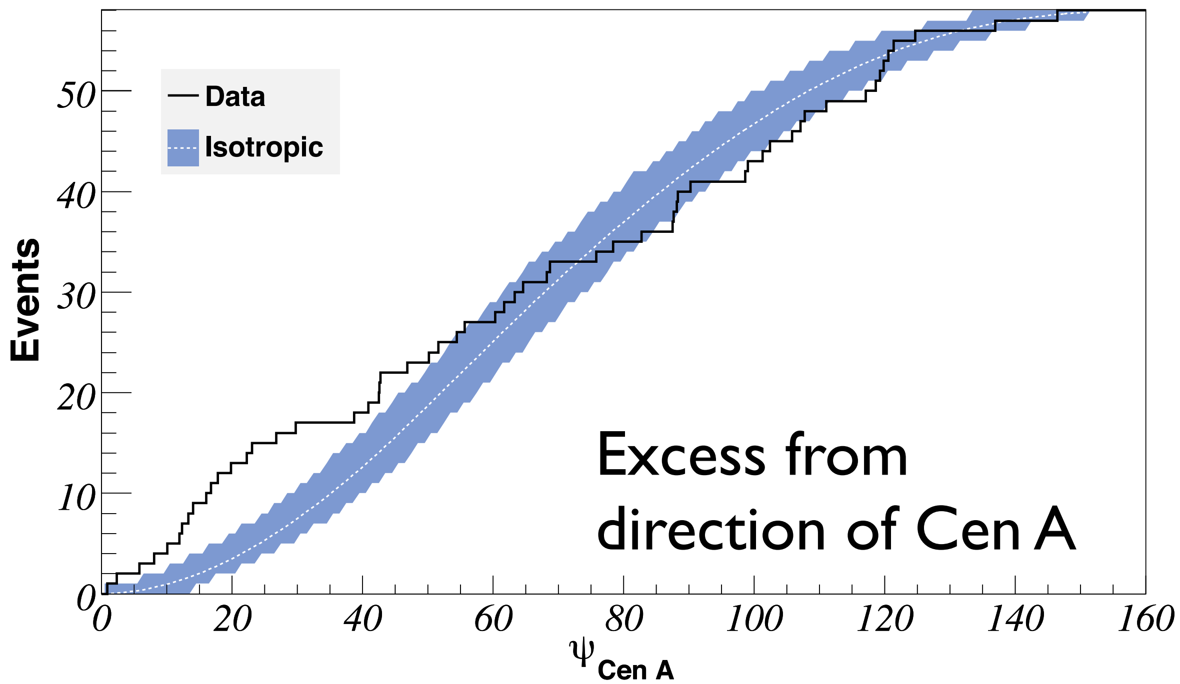


Period I: energy, angle, distance scan
Period II: prescription & Science publication
Period III: until March 2009

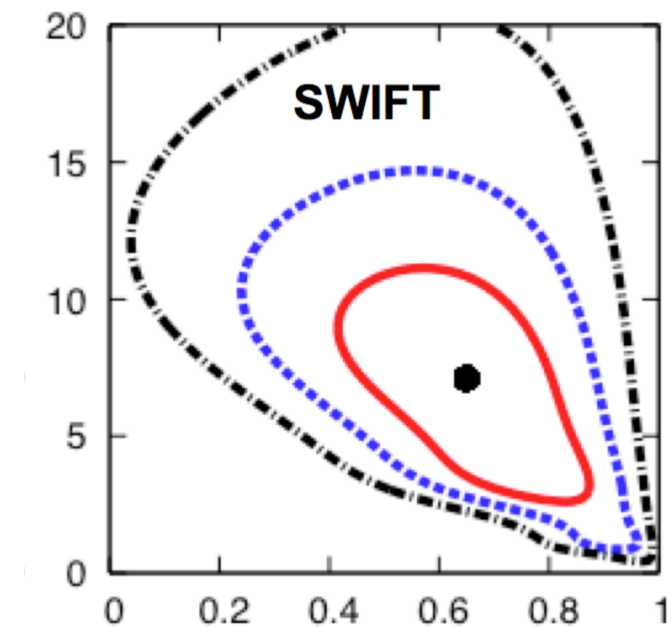


Period	Exposure	GP	N	k	k_{iso}	P
I	4390	unmasked	14	9	2.9	
		masked	10	8	2.5	
II	4500	unmasked	13	9	2.7	2×10^{-4}
		masked	11	9	2.8	1×10^{-4}
III	8150	unmasked	31	8	6.5	0.33
		masked	24	8	6.0	0.22
II+III	12650	**unmasked**	**44**	**17**	**9.2**	$\mathbf{6 \times 10^{-3}}$
		masked	35	17	8.8	2×10^{-3}
I+II	8890	unmasked	27	18	5.7	
		masked	21	17	5.3	
I+II+III	17040	unmasked	58	26	12.2	
		masked	45	25	11.3	

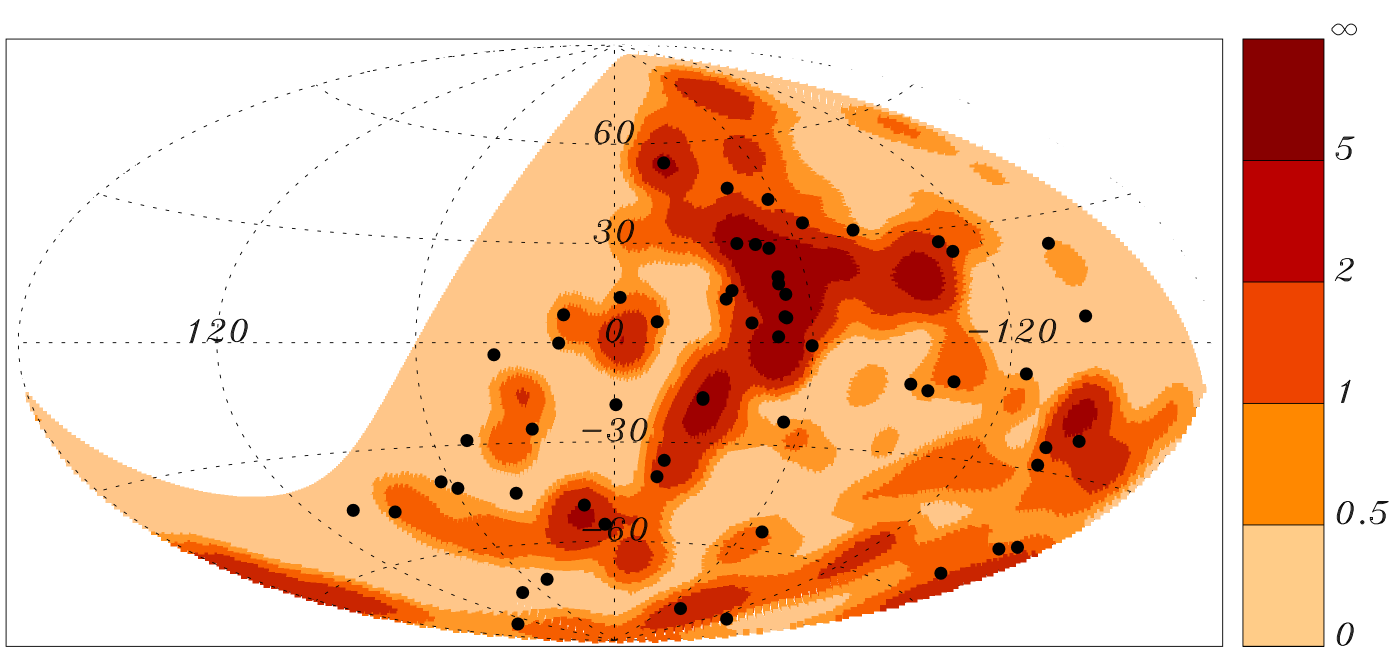
A posteriori analysis of arrival directions

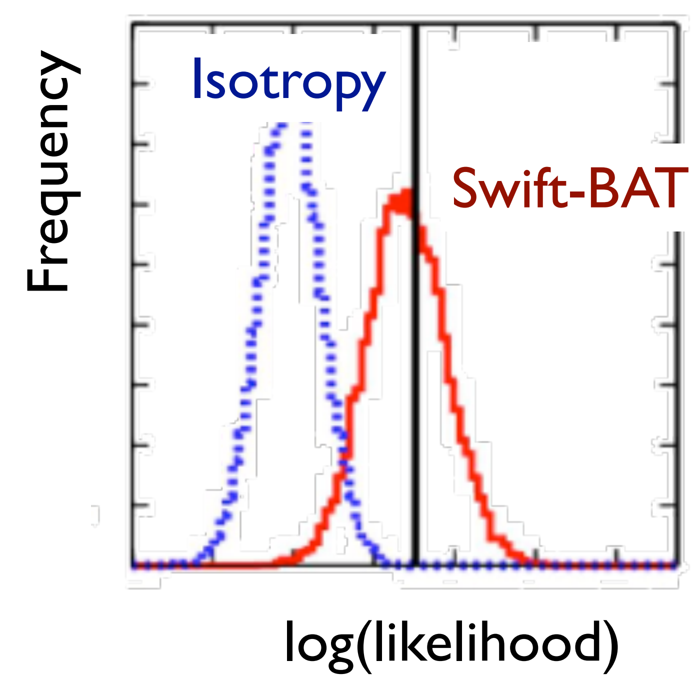


Parameter optimization



Example: Swift-BAT, volume limited, 5° smoothing



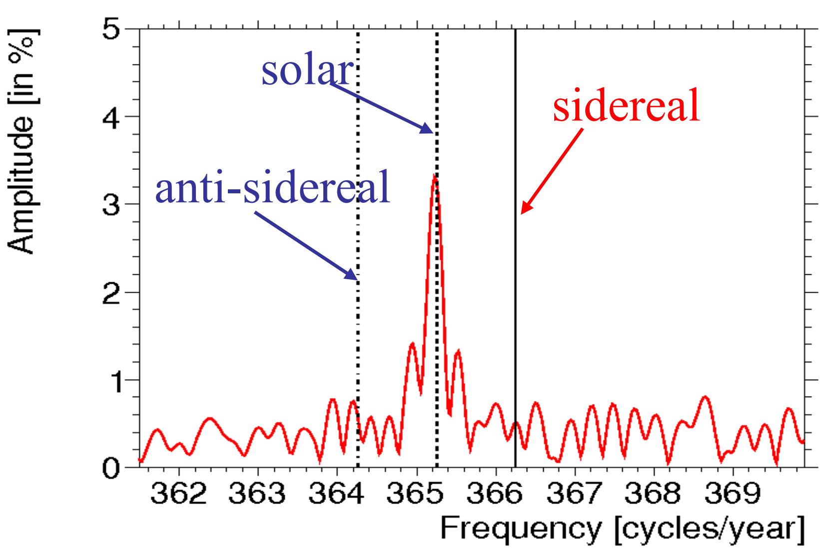


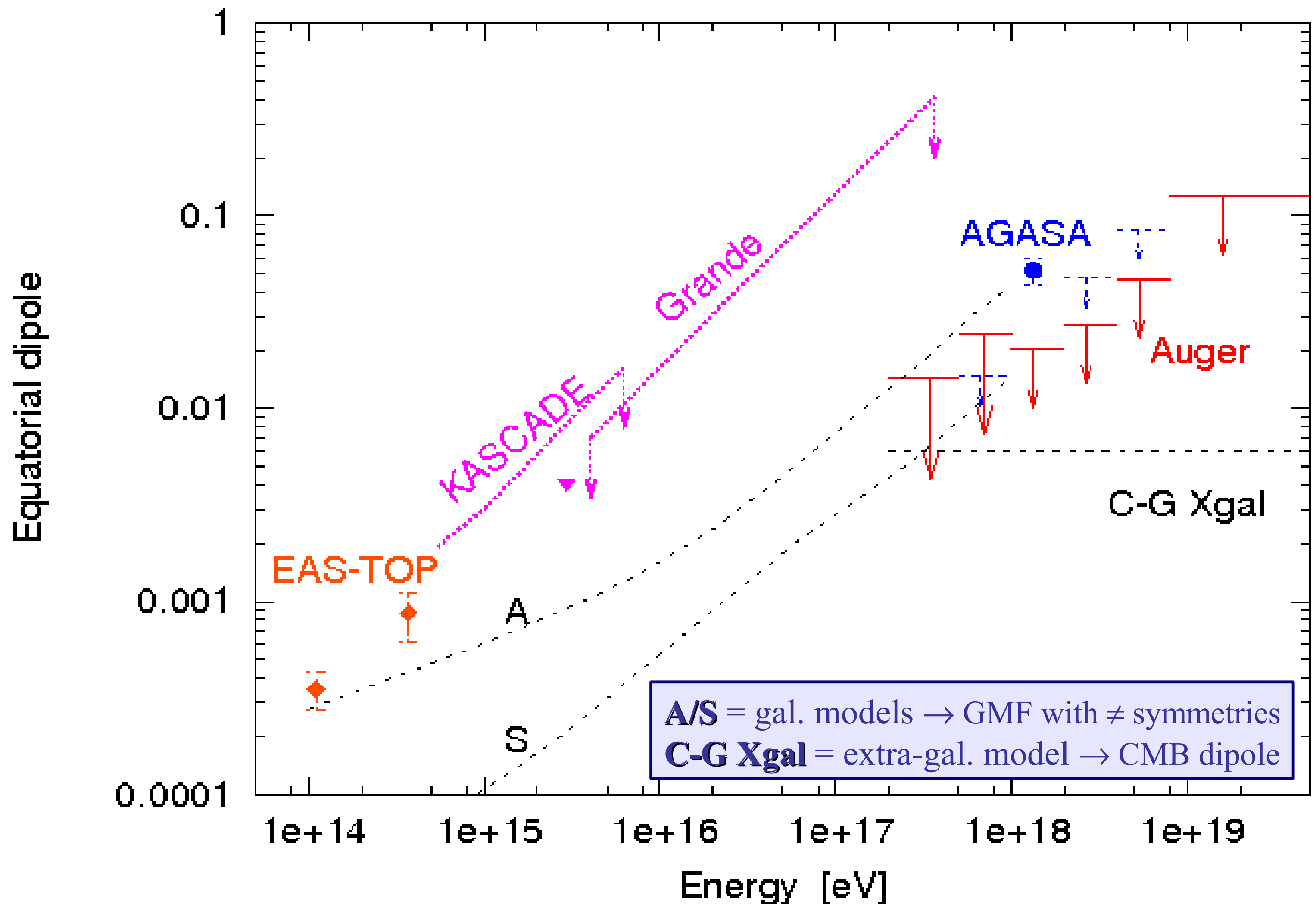
All data used in analysis, including period I

Large scale anisotropy (dipole search)

Different methods:

Fourier analysis
Rayleigh analysis
East-West method



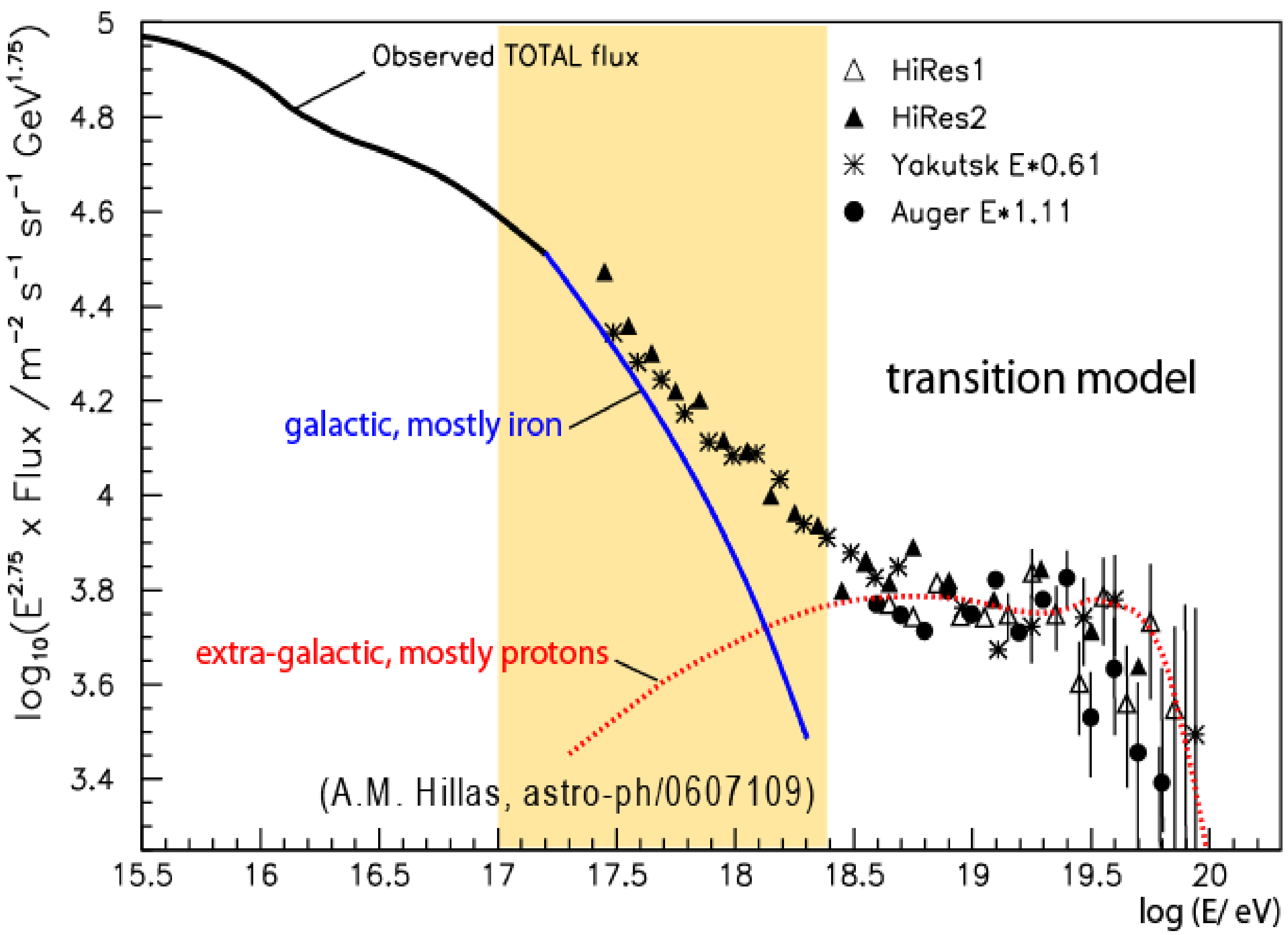


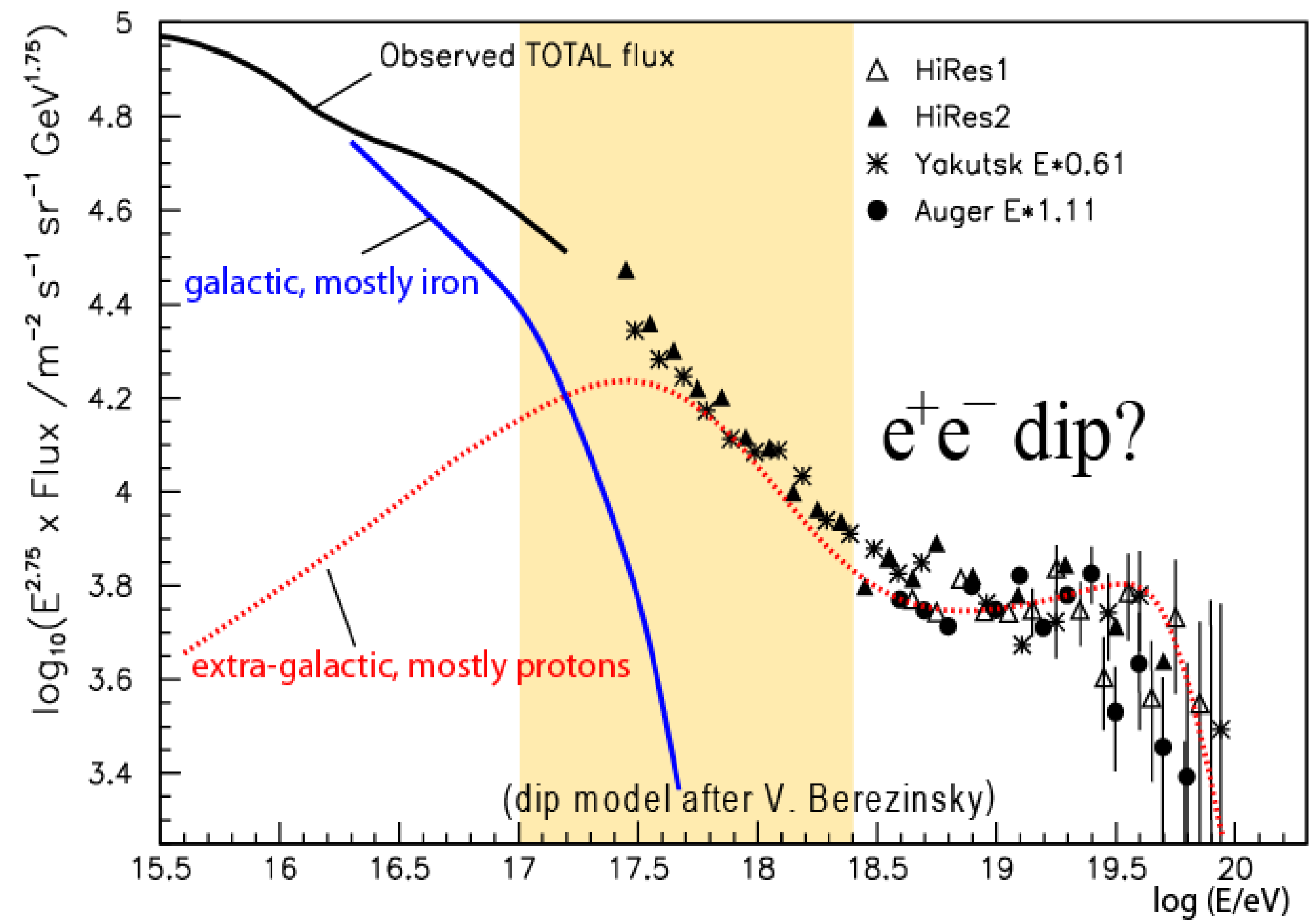
Energy range [EeV]	*Rayleigh analysis*			*E-W method*			*upp.limit [%]* (99%c.l.)
	r_{sid}[%]	s_R[%]	Prob [%]	r_{sid}[%]	s_{EW}[%]	Prob [%]	
all enegies				0.48	0.27	19.5	1.05
0.2 - 0.5				0.25	0.43	84.2	1.19
0.5 - 1				1.08	0.44	4.8	2.03
1 – 2	0.90	0.32	1.8	0.77	0.65	49.9	1.59
2 – 4	0.79	0.64	45.8	1.65	1.33	46.3	2.12
4 – 8	0.71	1.33	86.6	5.05	2.73	18.0	3.66
> 8	5.36	2.05	3.3	2.76	4.08	79.5	9.79

Auger ICRC 2009

Enhancements

Transition from galactic to extragalactic sources





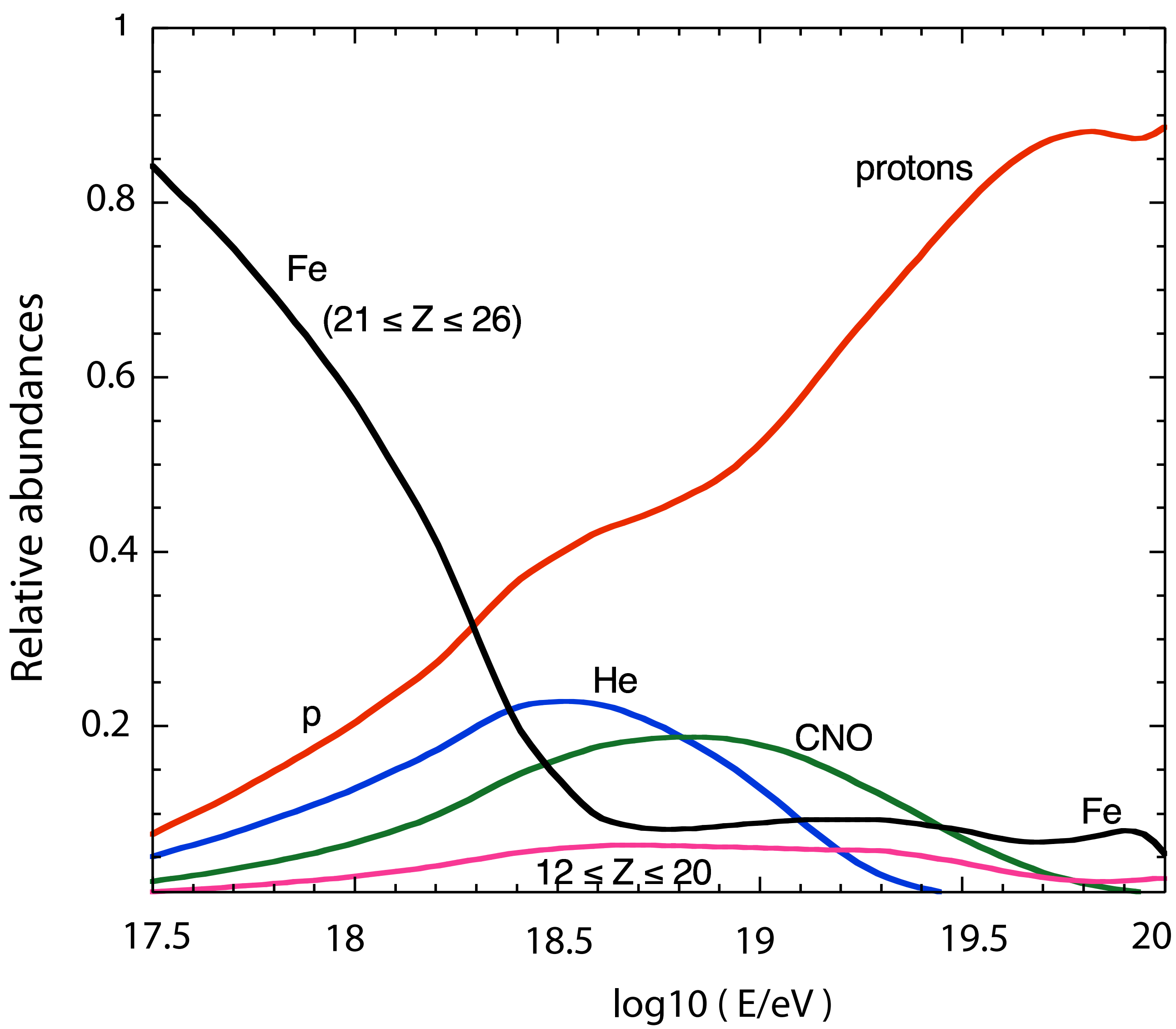
Hillas:
- Ankle is transition galactic to extragalactic cosmic rays
- Injection spectrum ***dN/dE ~ $E^{-2.3}$***

Berezinsky et al.:
- Ankle is feature due to extragalactic proton propagation
- Injection spectrum ***dN/dE ~ $E^{-2.7}$***

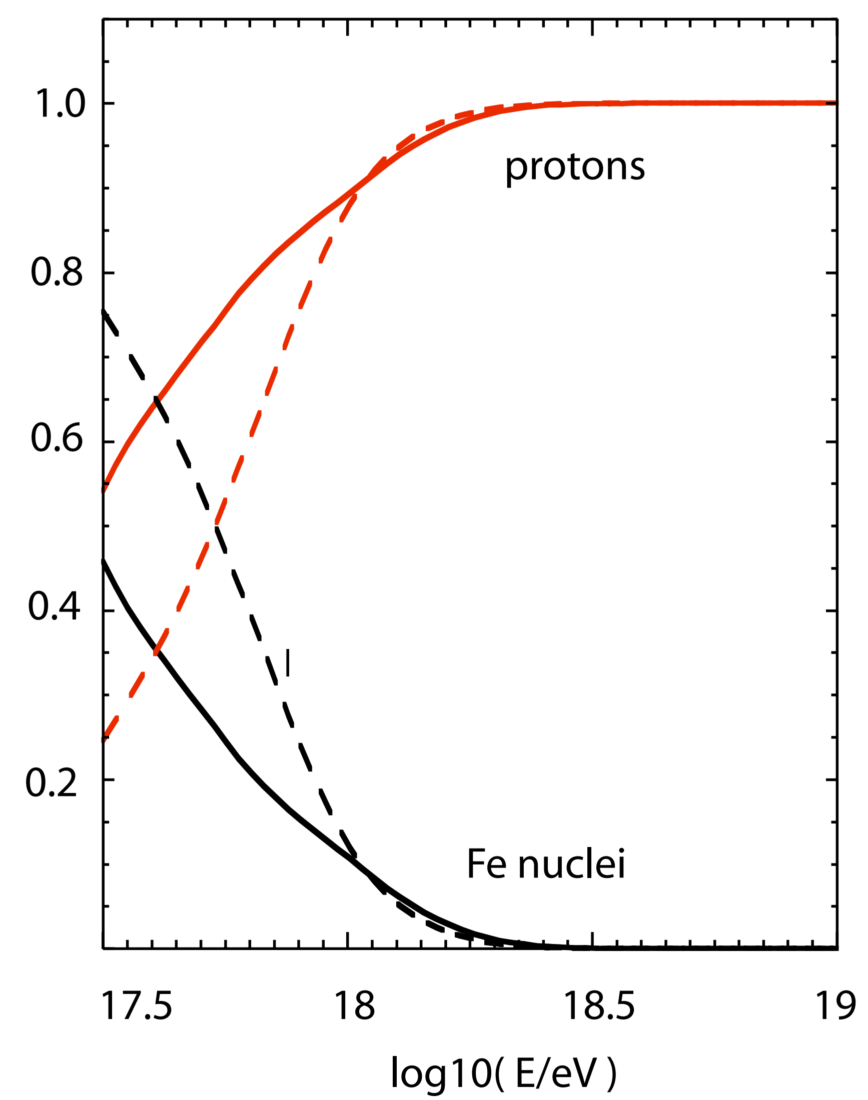
Flux very similar, composition different

Physics motivation: composition

Classic model of ankle



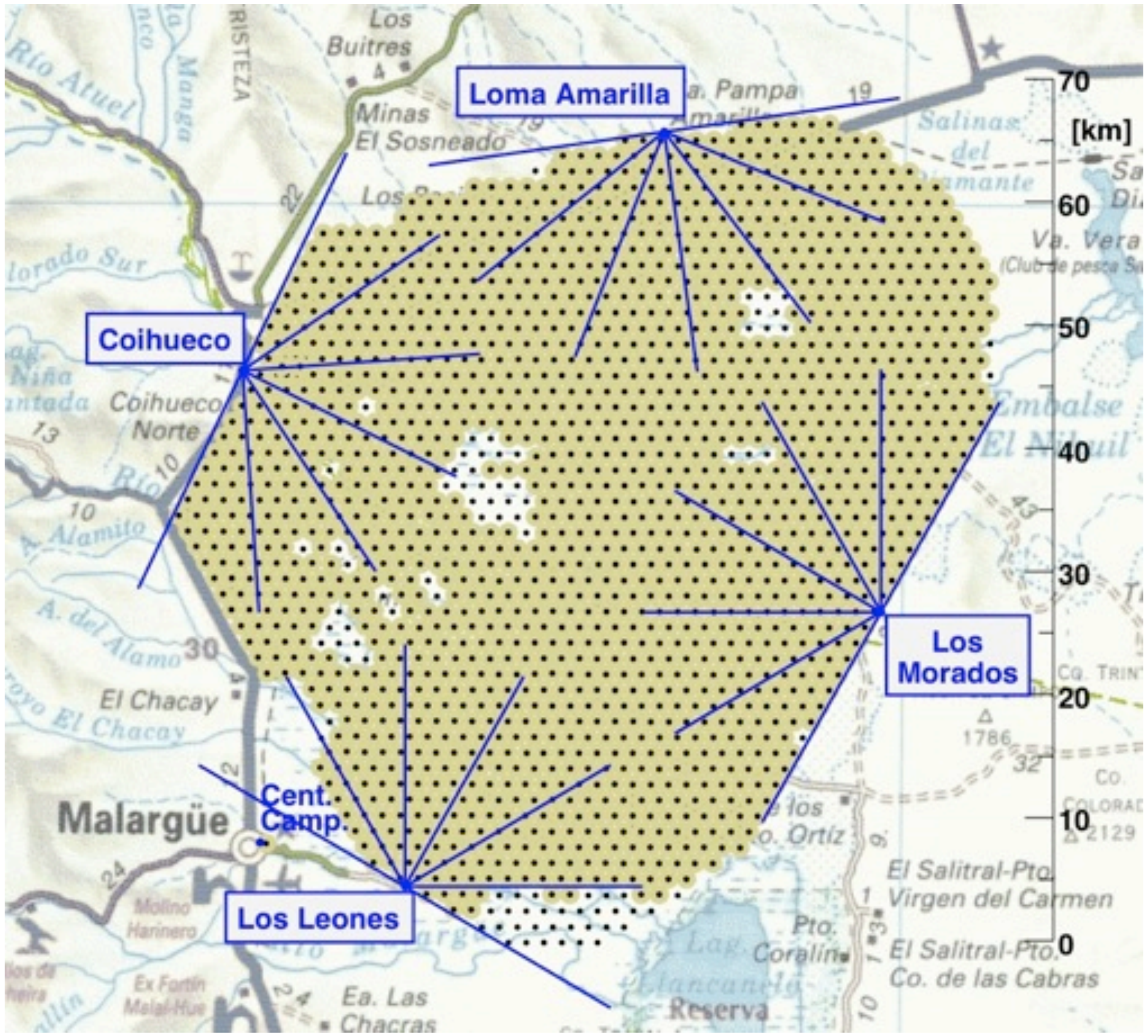
Pair-prod. model



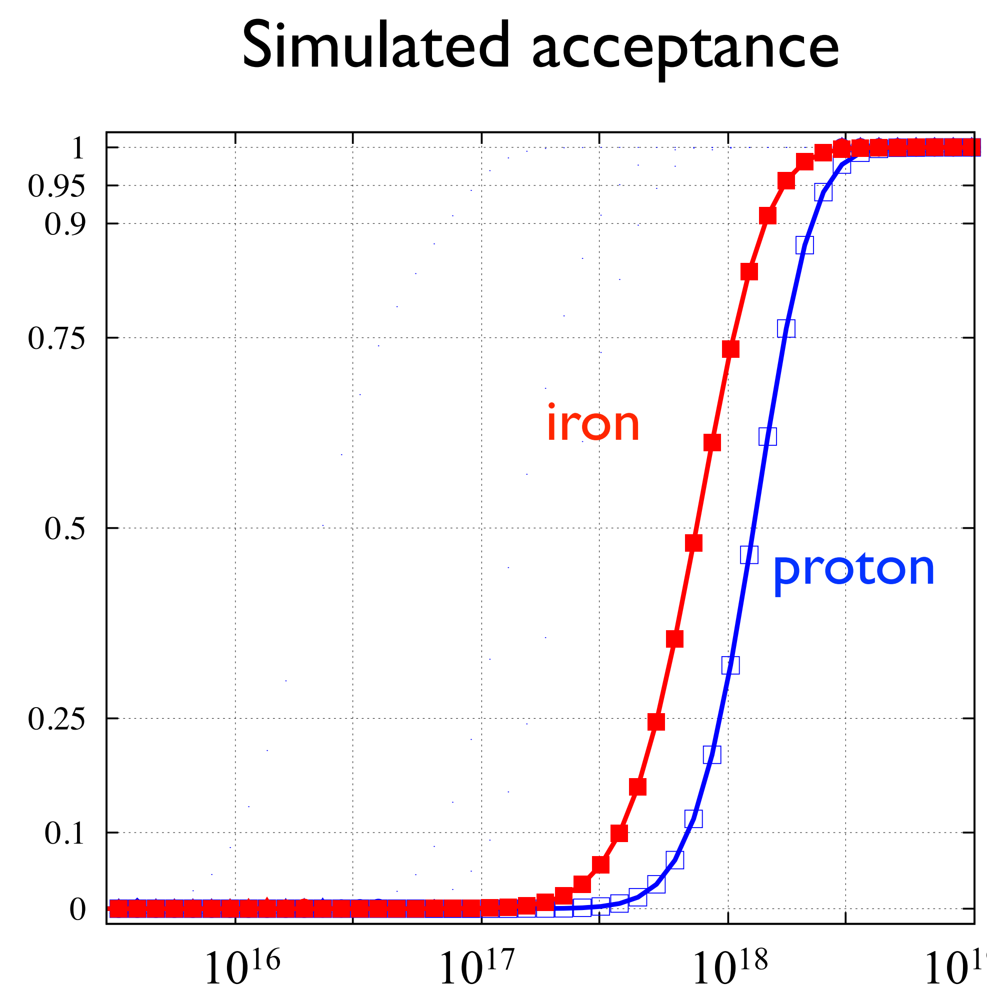
Measurement of flux and composition in ankle region

(Allard et al., 2005; Aloisio et al. 2006)

Current surface detector threshold

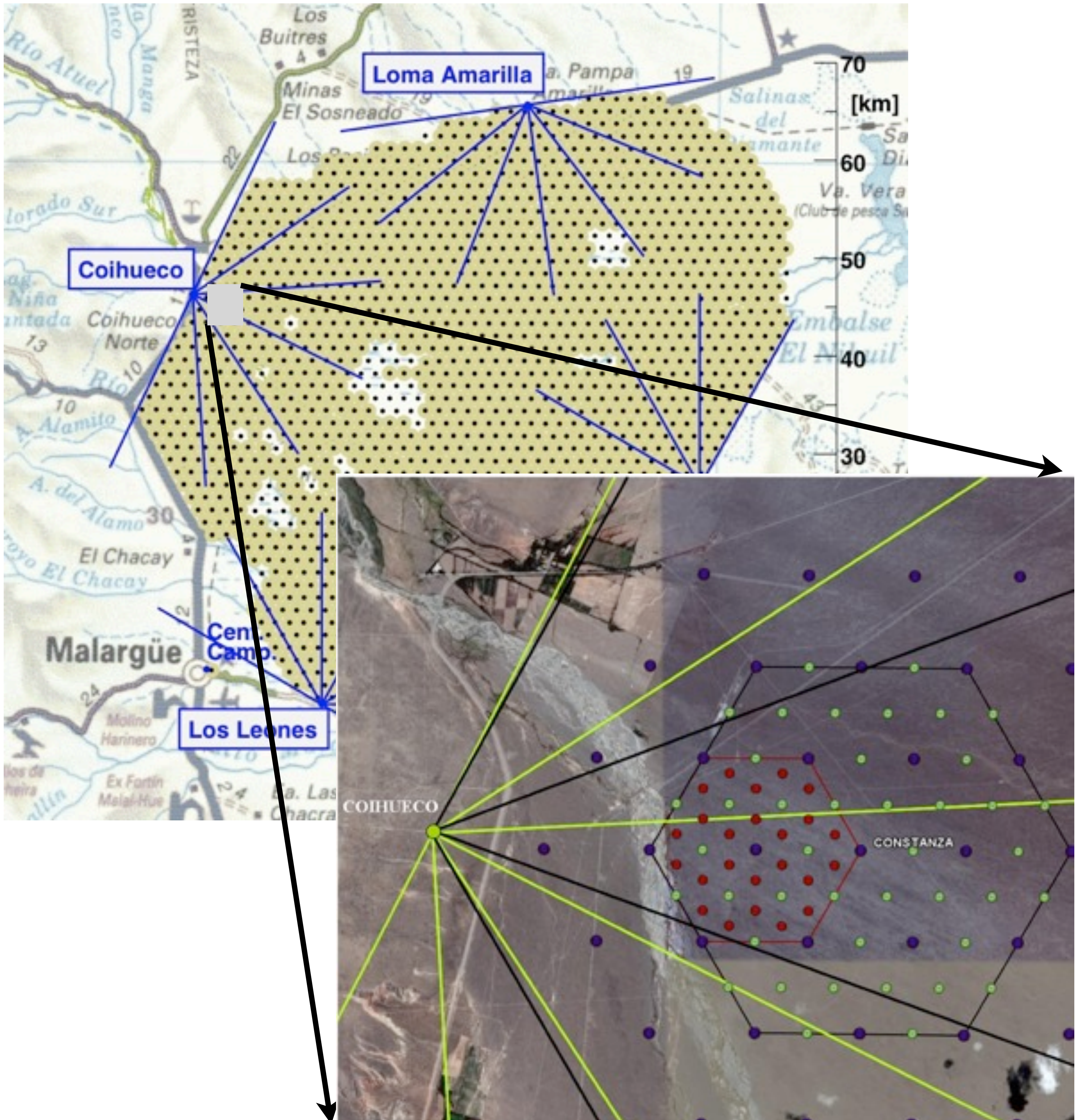


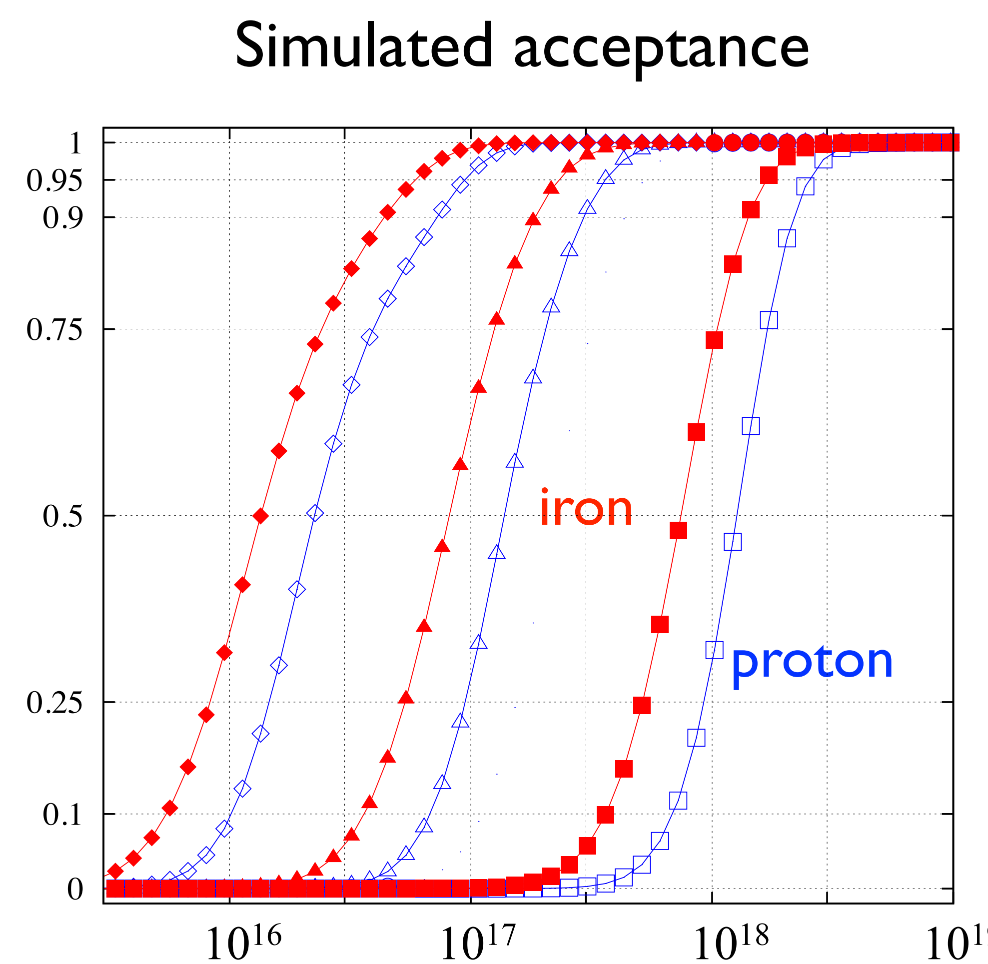
(Today: ~1663 SD units in field,
1634 with water, 1567 taking data)



Threshold for array ~$10^{18.5}$ eV
Composition dependence

Infill array of water Cherenkov detectors



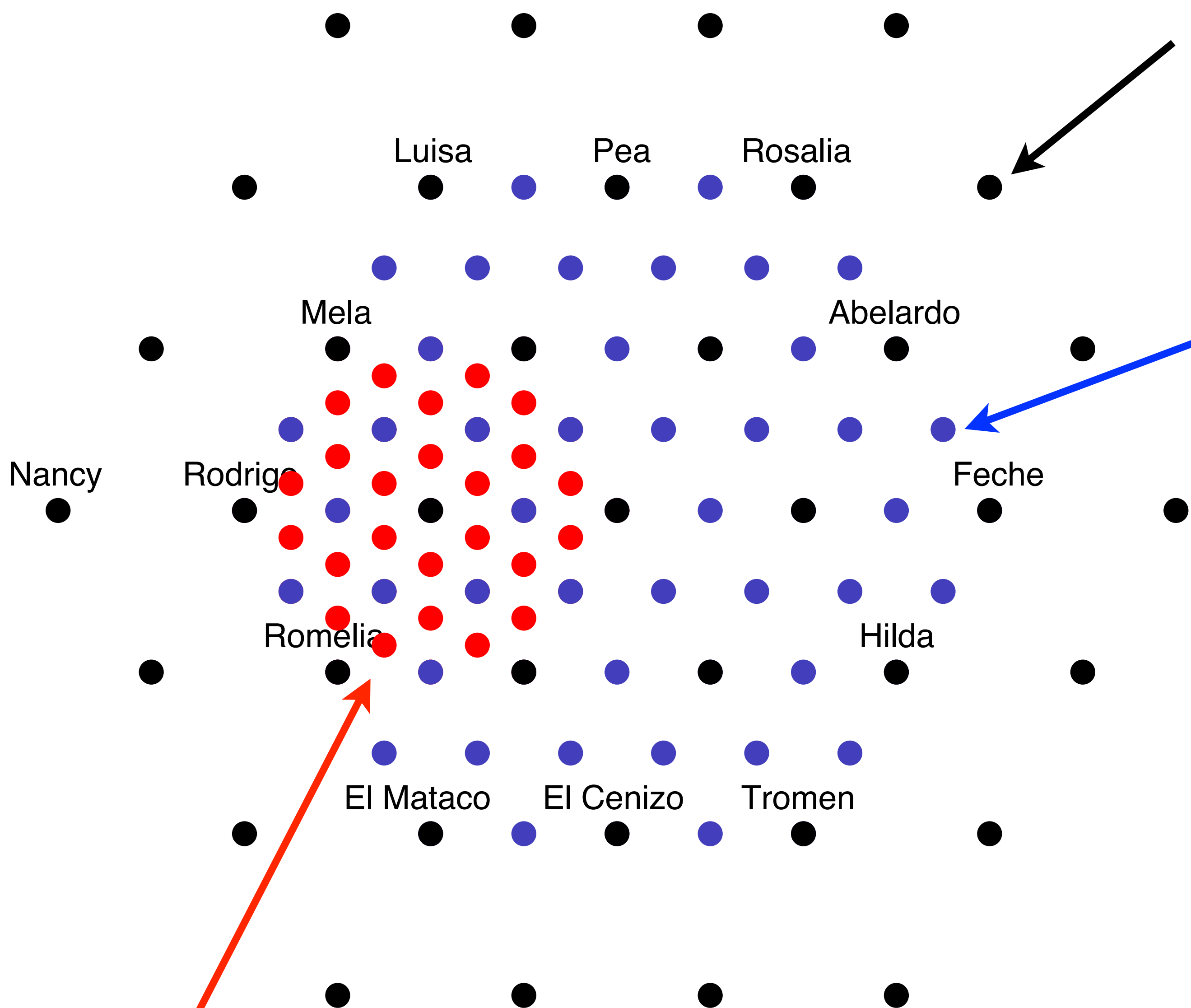


433m 750m 1500m

Threshold for
infill array ~10^{17} eV

AMIGA: Auger Muons and Infill for the Ground Array

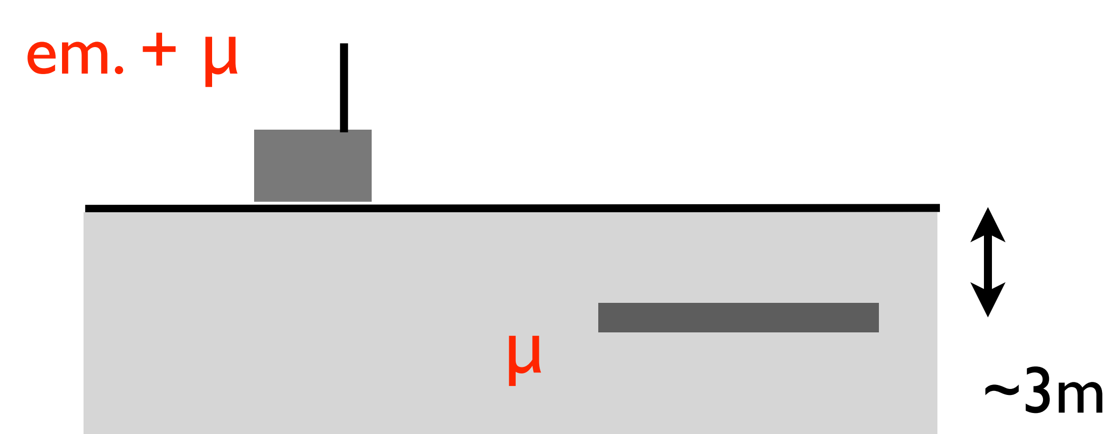
Existing tank array 1500m



Infill array 750m
42 additional detectors
Area ~ 23.5 km^2

Infill array 433m
24 additional detectors
Area ~ 5.9 km^2

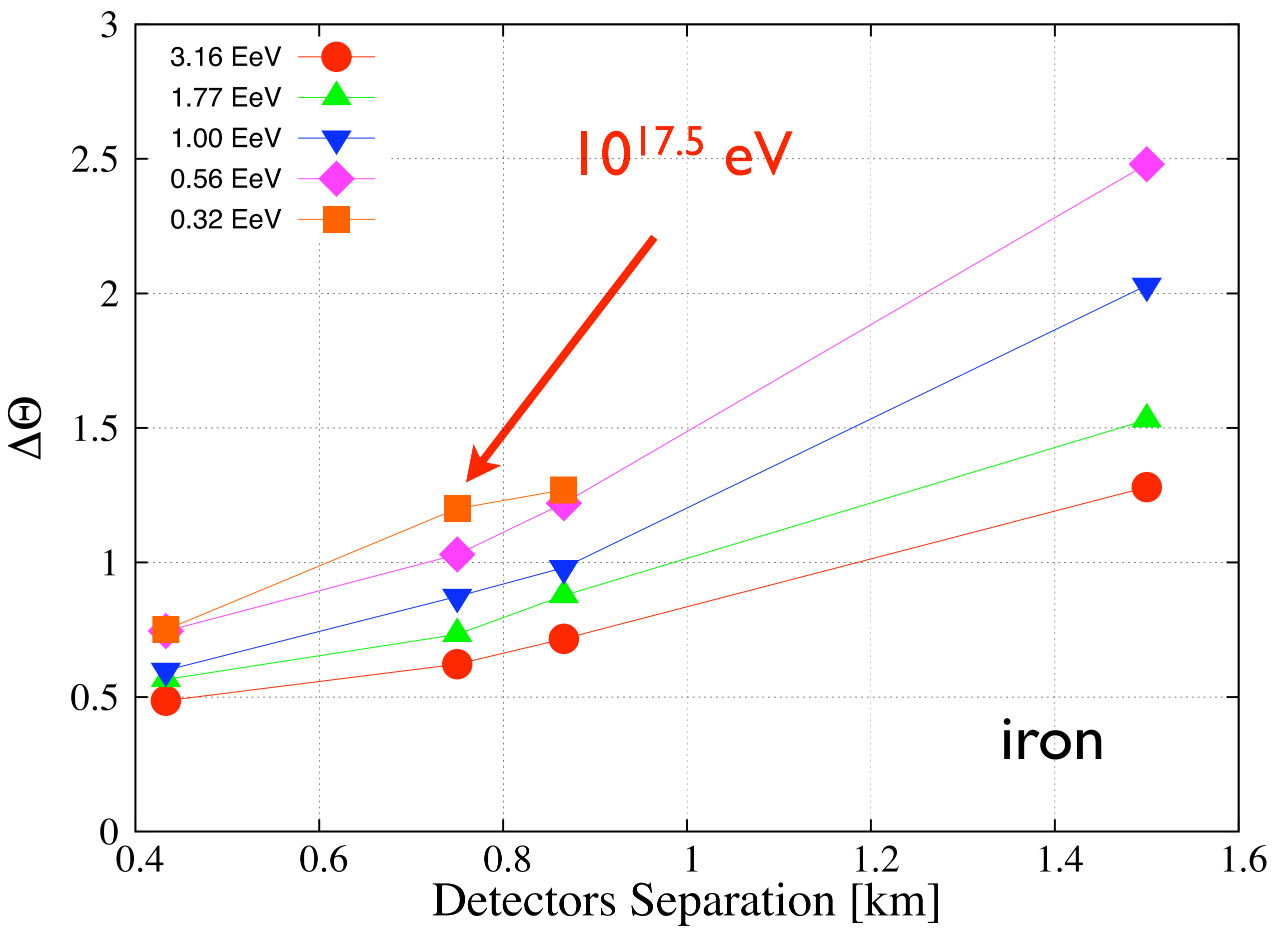
Each of the 85 detectors:
pair of Cherenkov tank
and muon counter



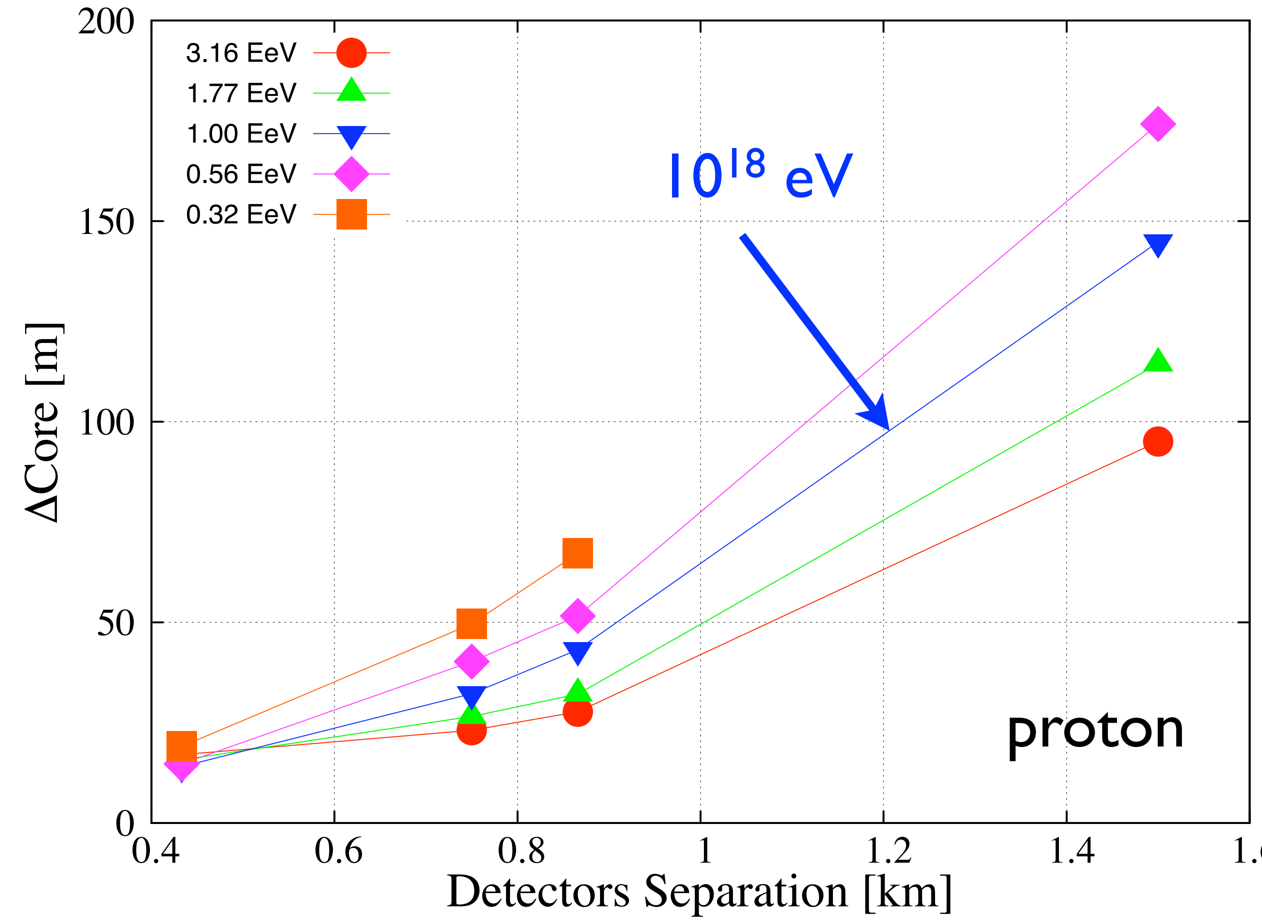
Shower reconstruction with infill Cherenkov tanks

Examples: simulations for proton and iron showers at 30°

Arrival direction reconstruction



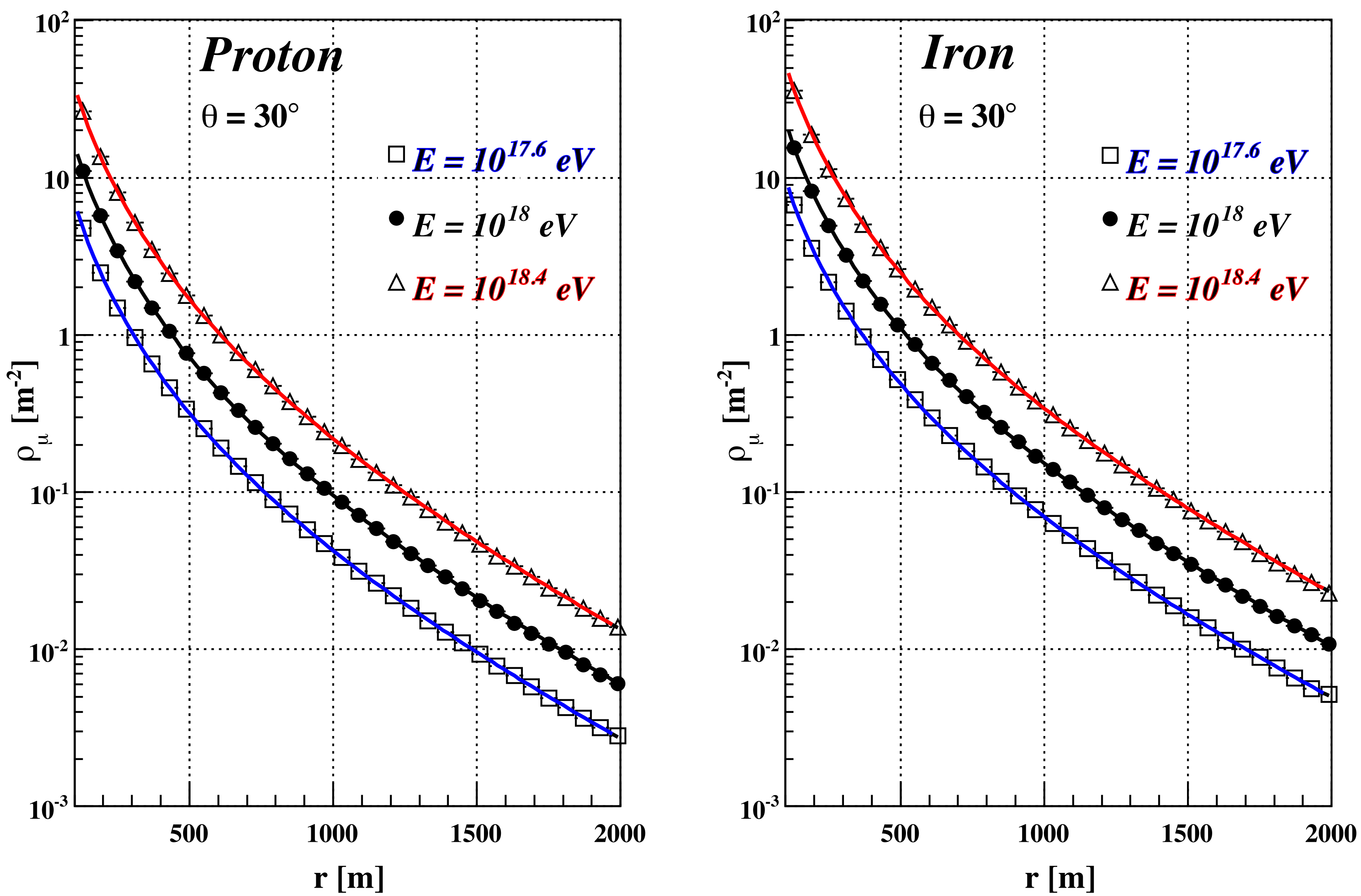
Core position reconstruction



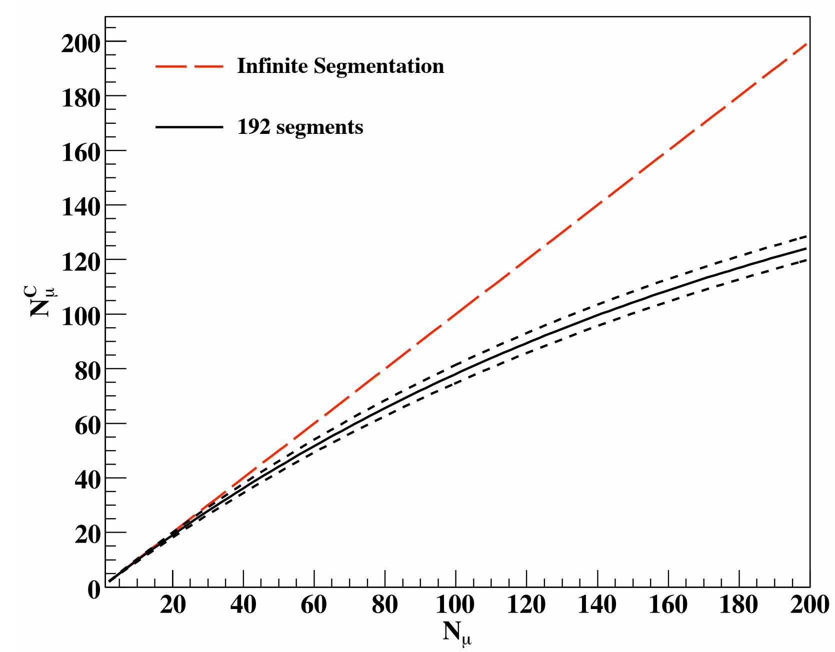
(Medina et al., NIM 566, 2007)

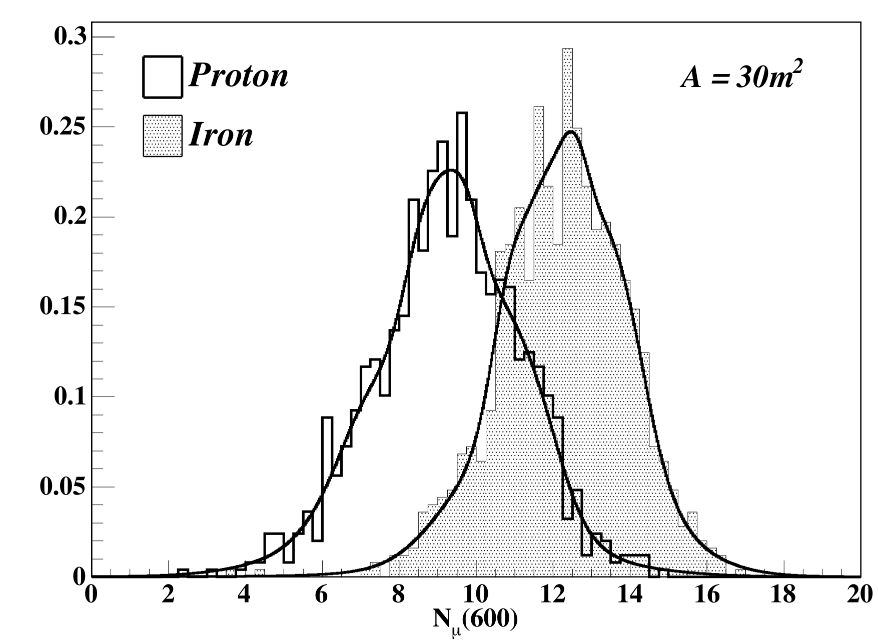
Expected performance of muon detectors

Lateral distribution of muons



three-module counter



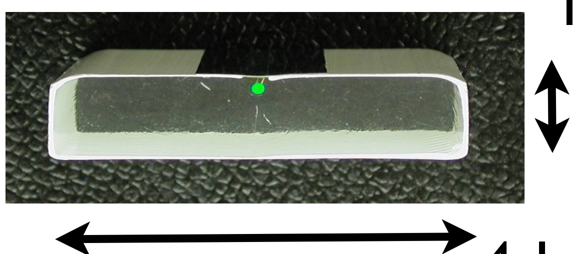


Example: reconst. muon numbers for 10^{18} eV showers at 30°

(Supanitsky et al., to be published)

AMIGA scintillator design

MINOS-type scintillators

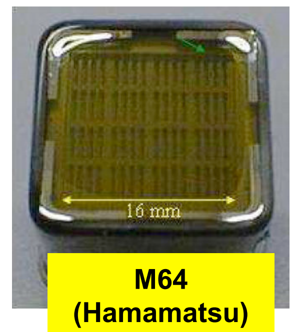


1cm

4.1cm

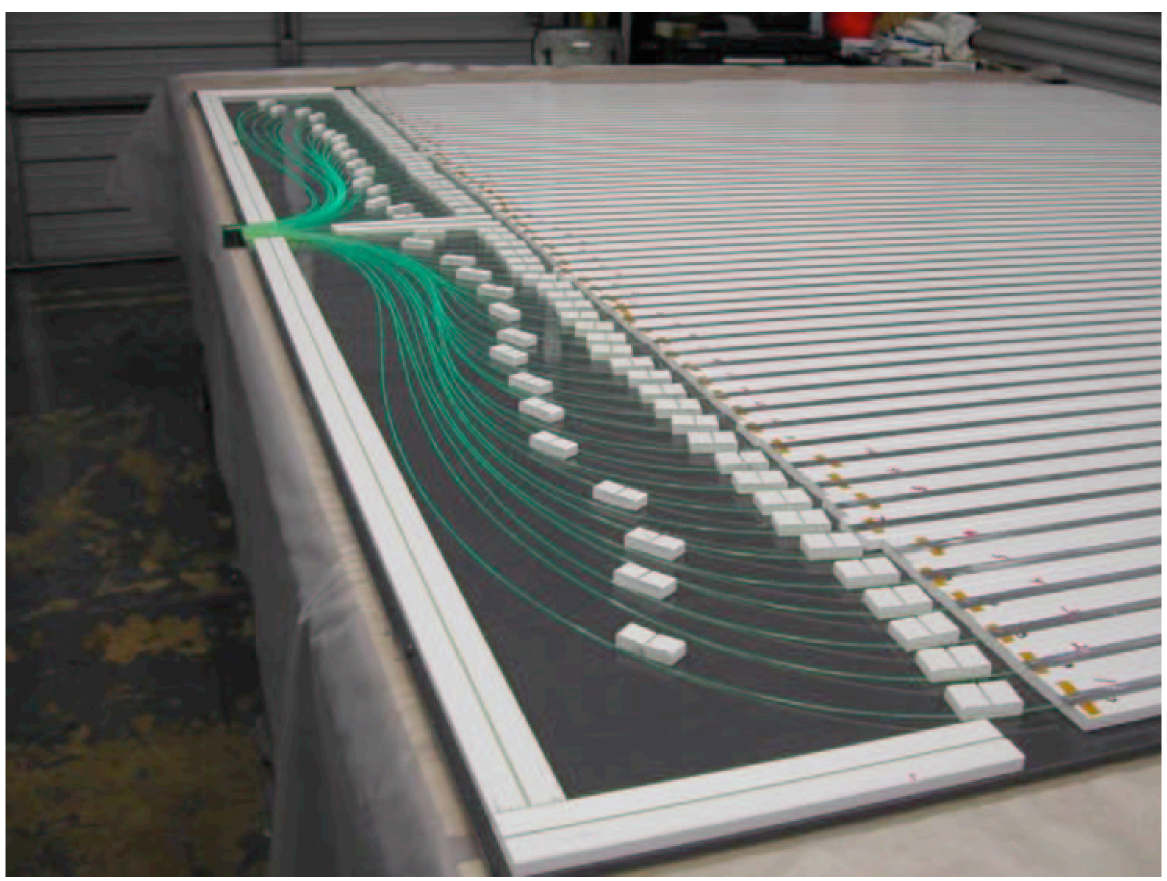
Multi-anode PMT:

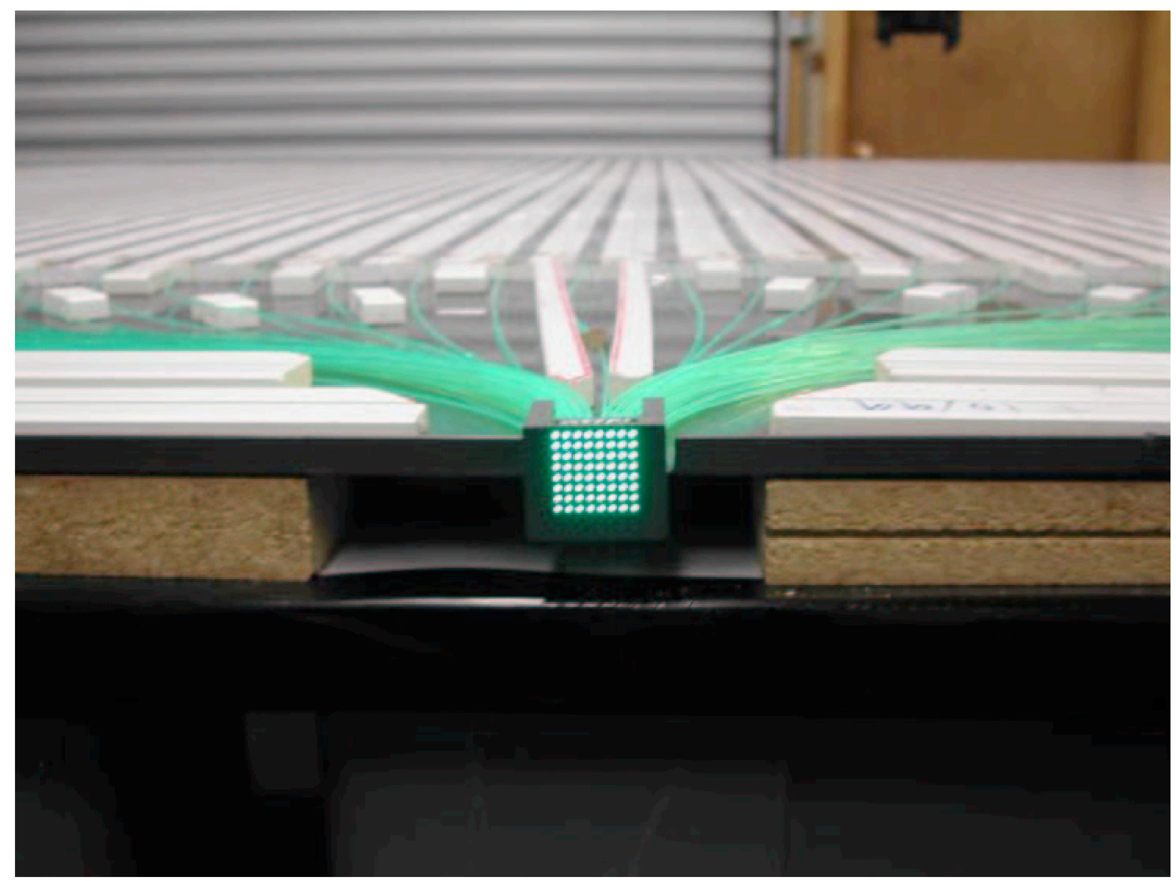
64 pixels (2 x 2 mm^2)



Detector station:

2 modules, each 2.6 x 4 m^2
2 modules, each 2.6 x 2 m^2
PVC housing
25 ns, 8 bit electronics
area ~ 31.5m^2



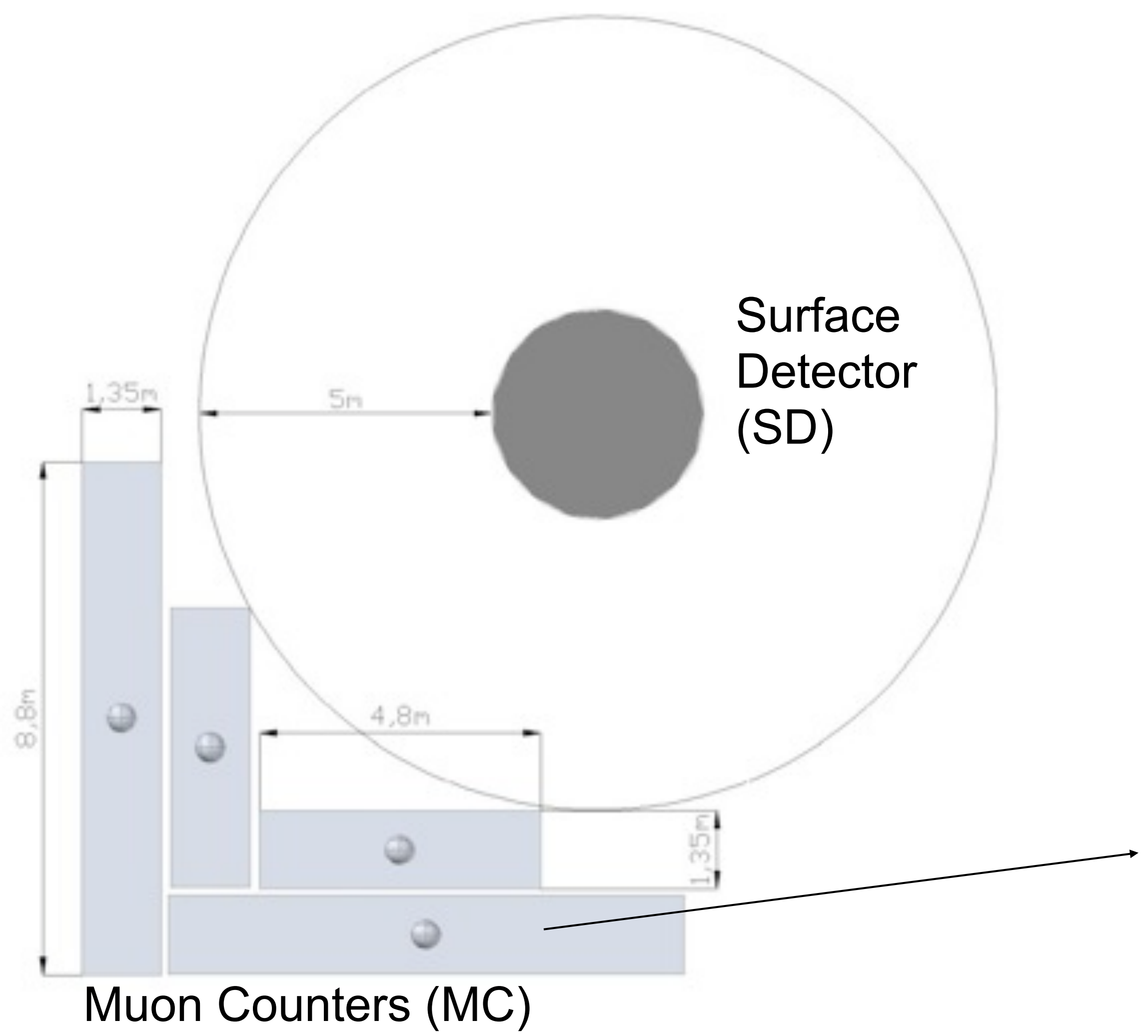


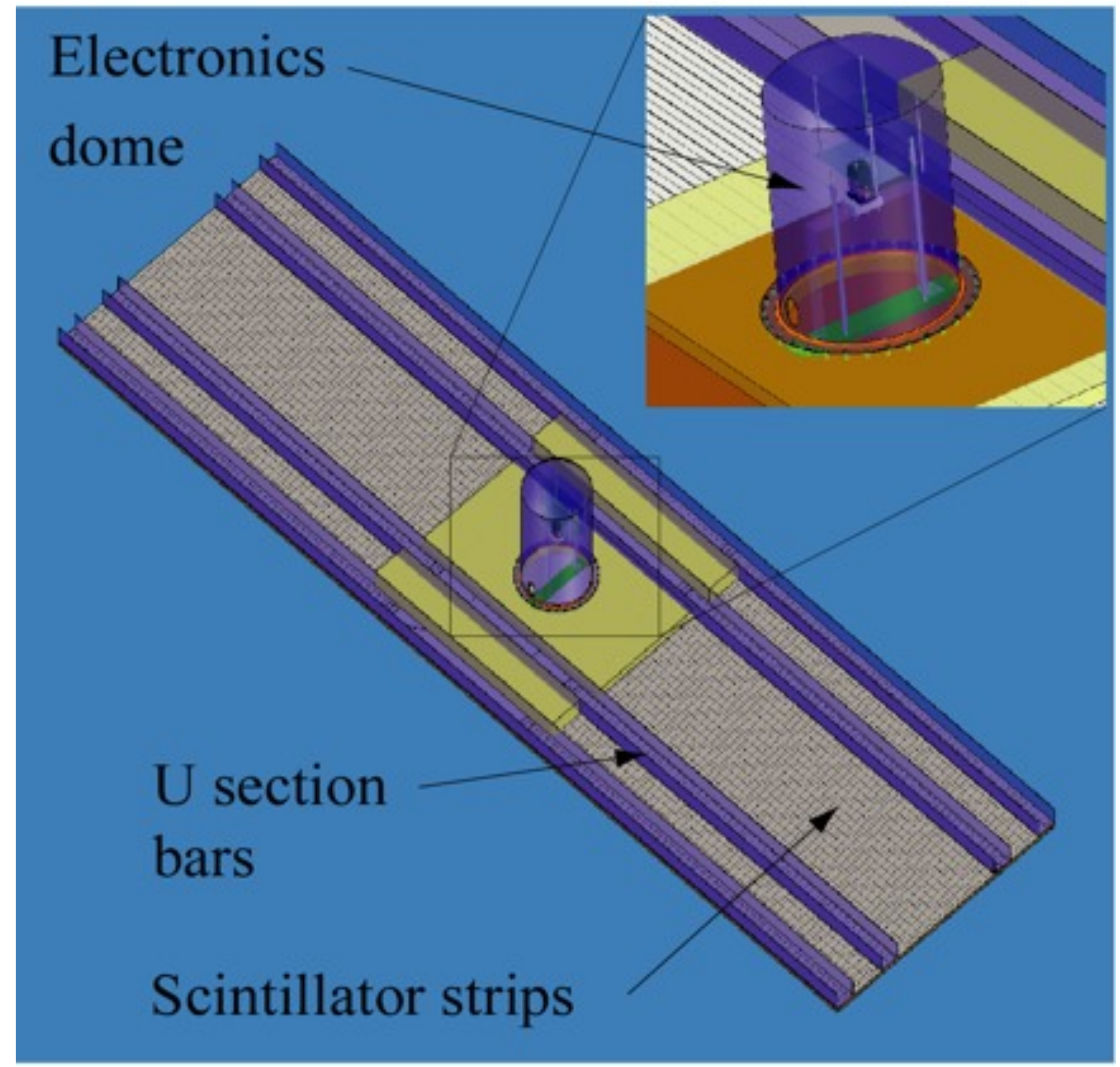
Extruded polystyrene doped with fluors, 14 pe per passing muon

AMIGA detector layout

Detectors have to have large area for counting

30 m² size
256 segments
Buried 2.25 m deep





Status of AMIGA unitary cell

December 2009

Status of AMIGA unitary cell

December 2009

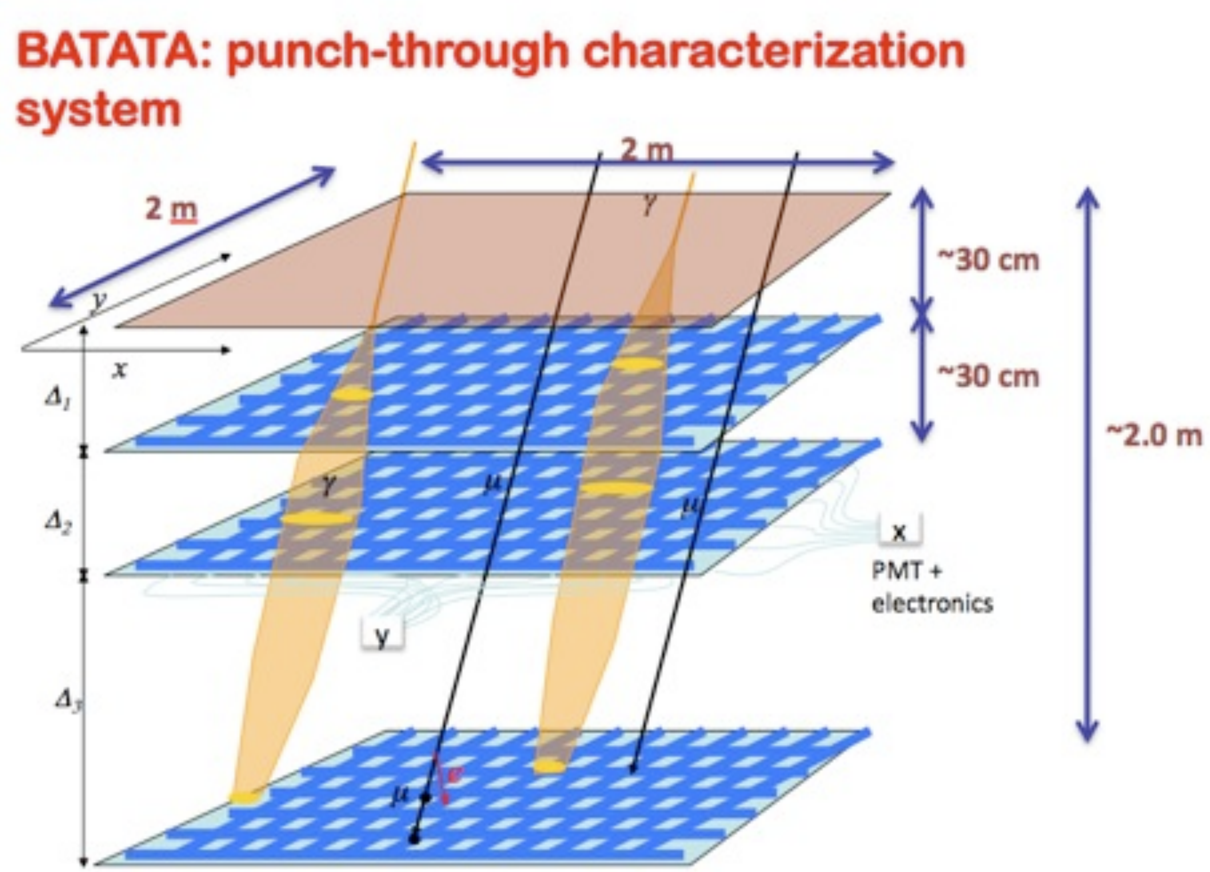
Status of AMIGA unitary cell

December 2009

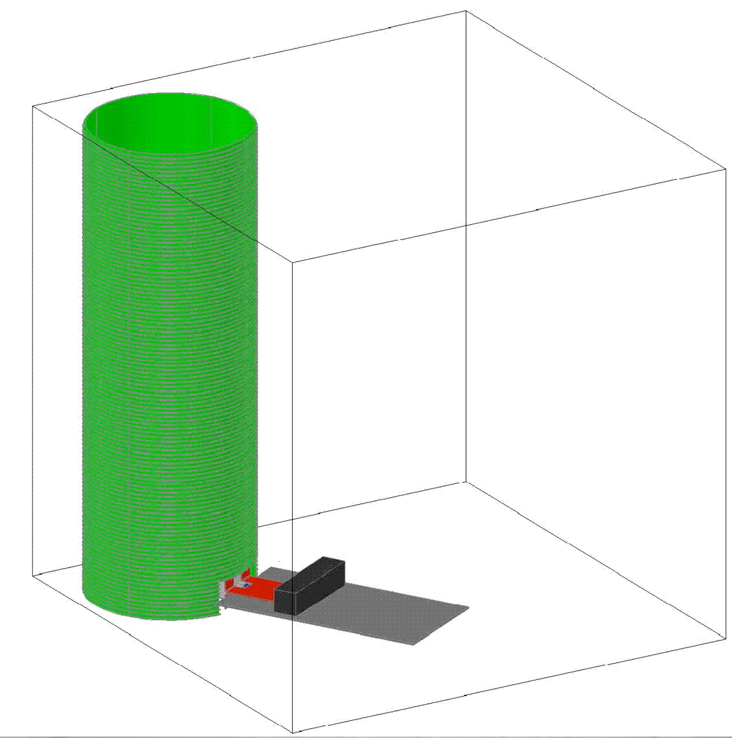
Status of AMIGA unitary cell

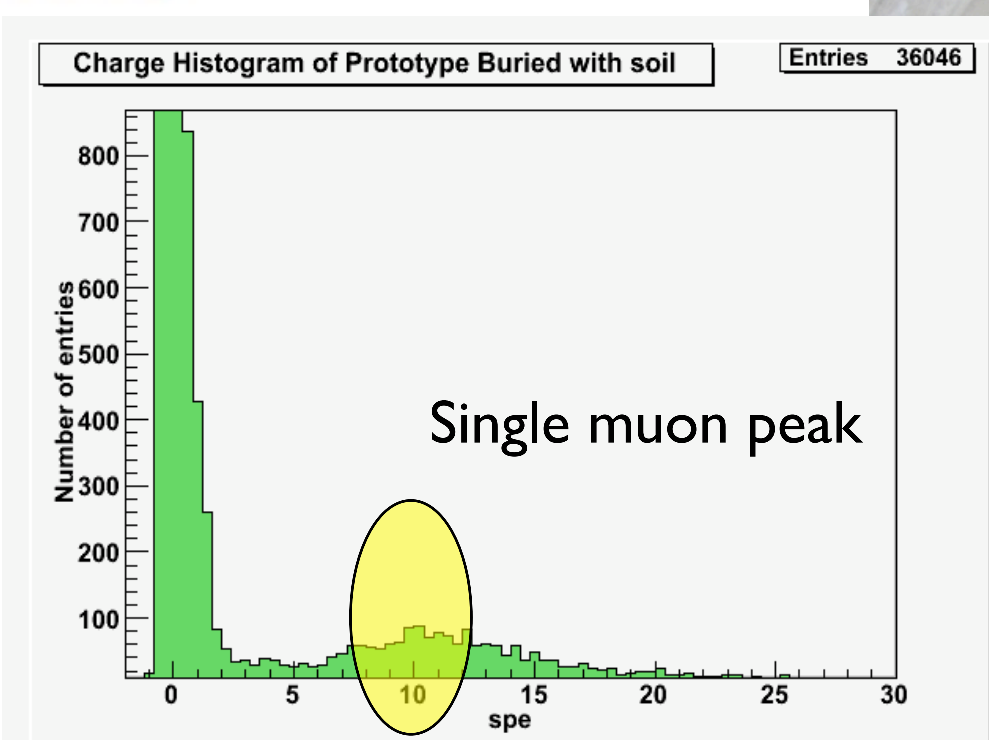
December 2009

AMIGA prototype development



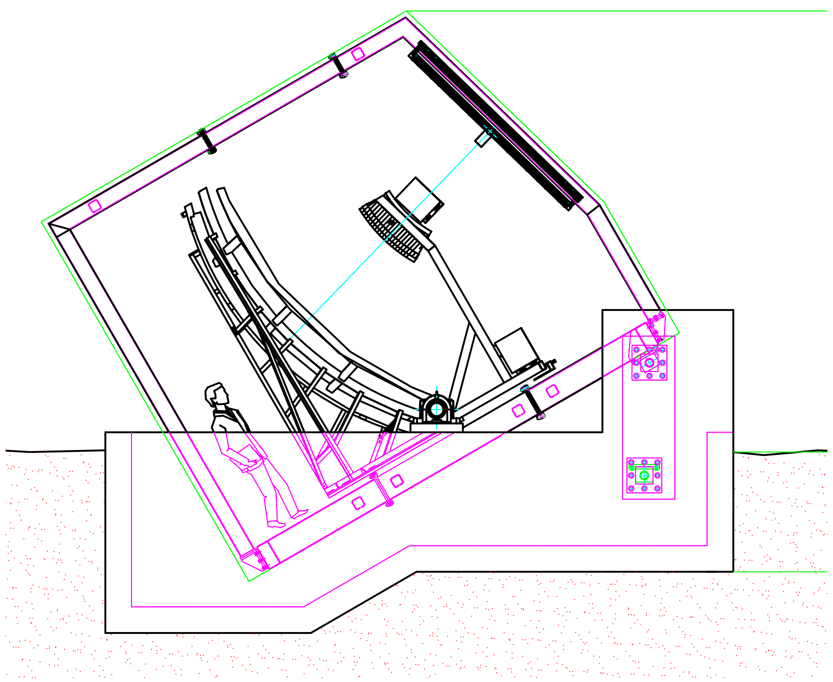
Buried scintillator prototype

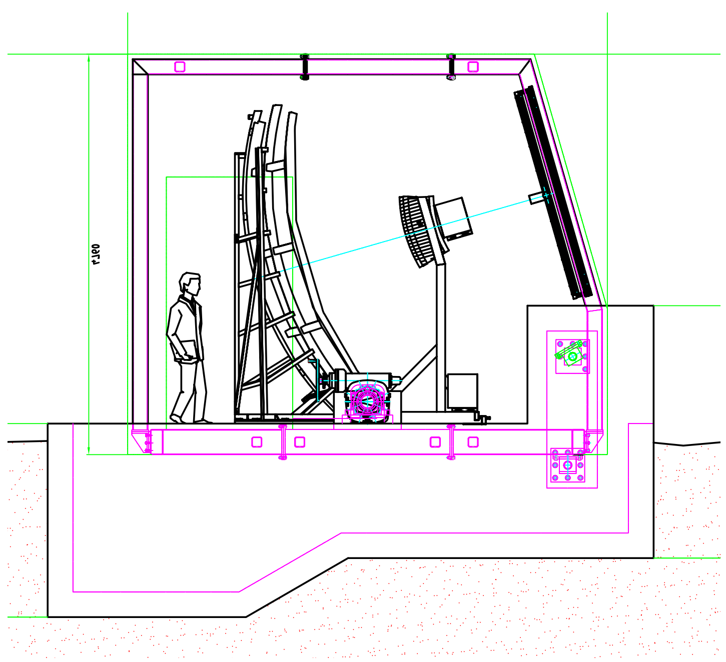


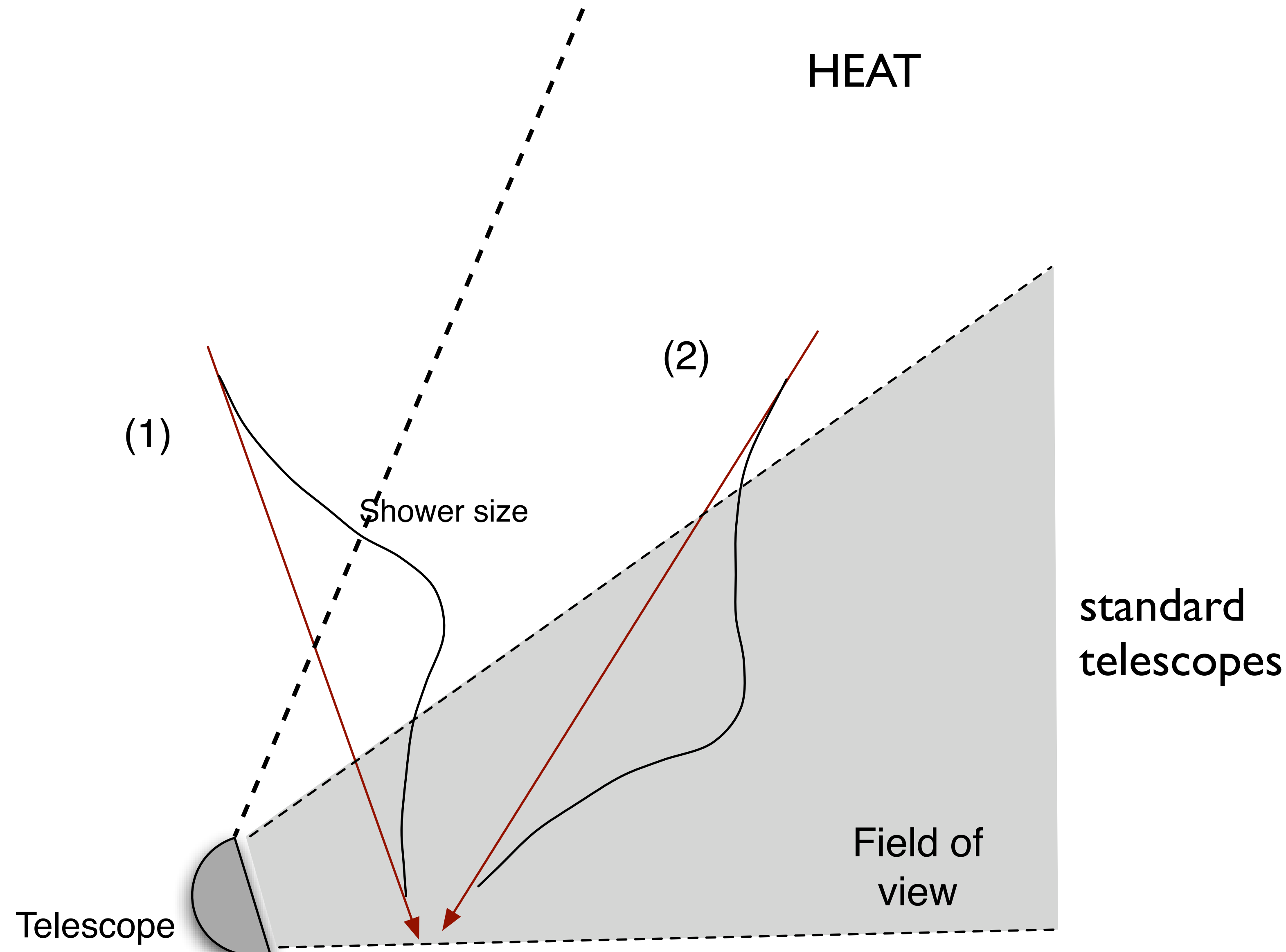


Energy threshold for muons 0.8 ~1 GeV

HEAT: High Elevation Auger Telescopes

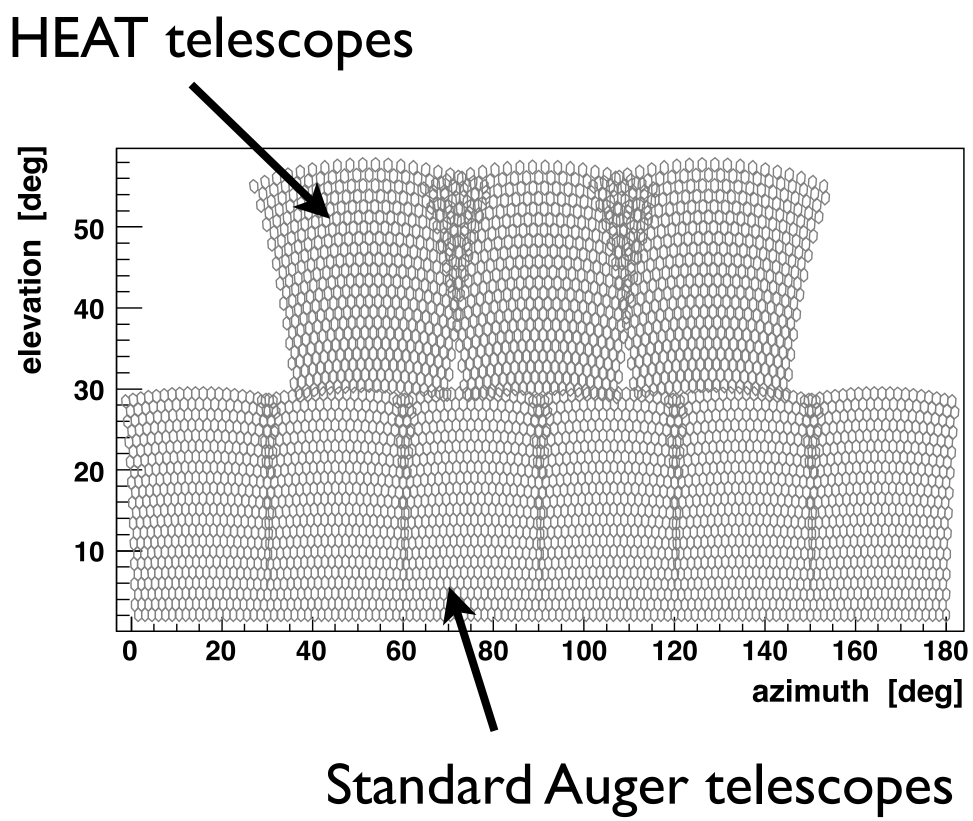




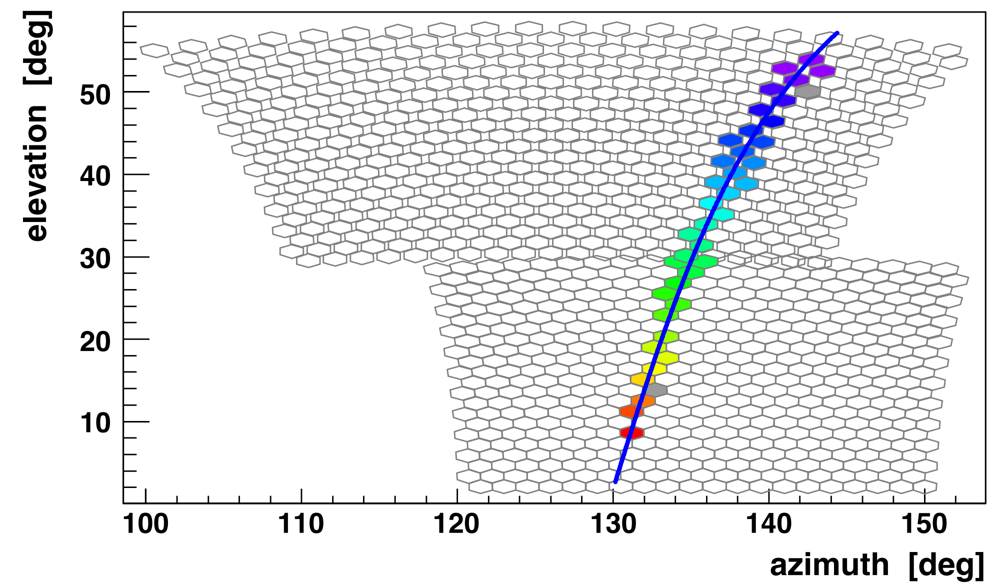


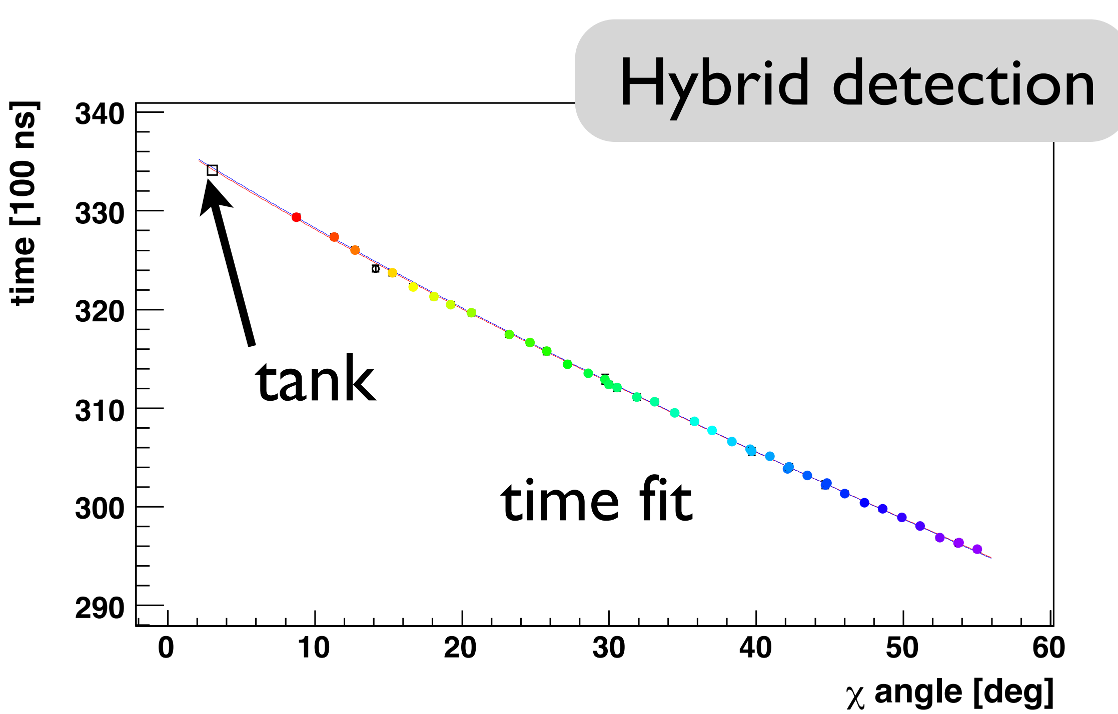
- 3 ``standard´´ Auger telescopes tilted to cover 30 - 60° elevation
- Custom-made metal enclosures
- Also prototype study for northern Auger Observatory

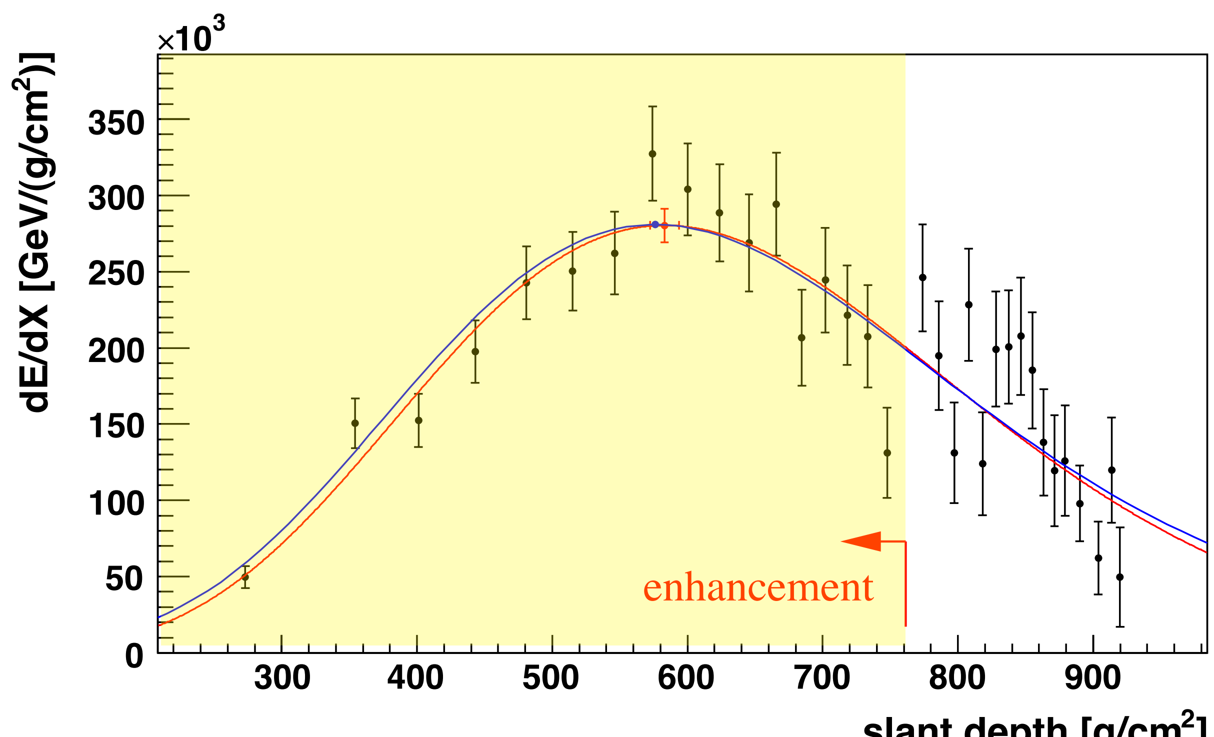
Simulation of HEAT telescopes



Simulated shower with core distance
R_p = 1.2 km, E = $10^{17.25}$ eV



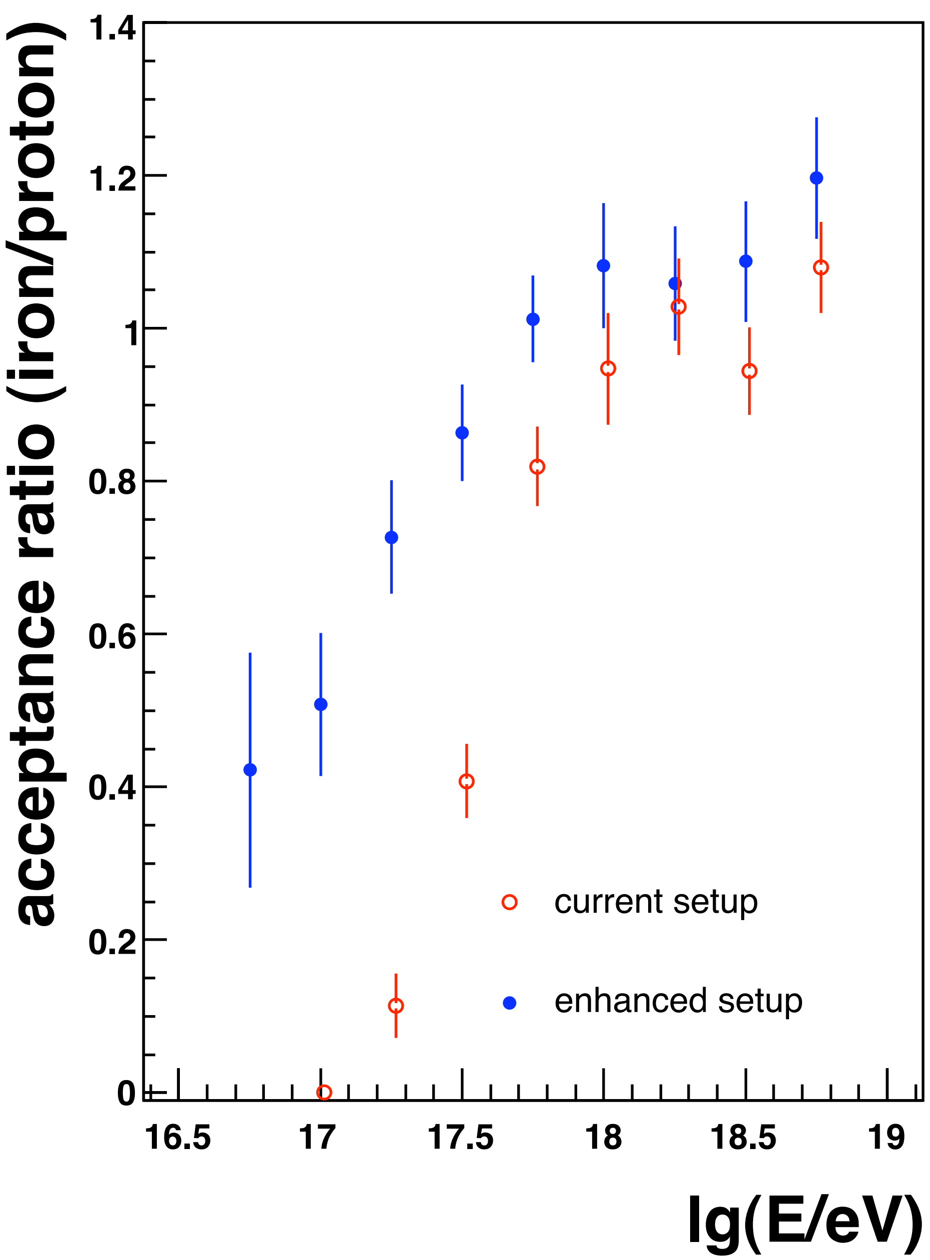


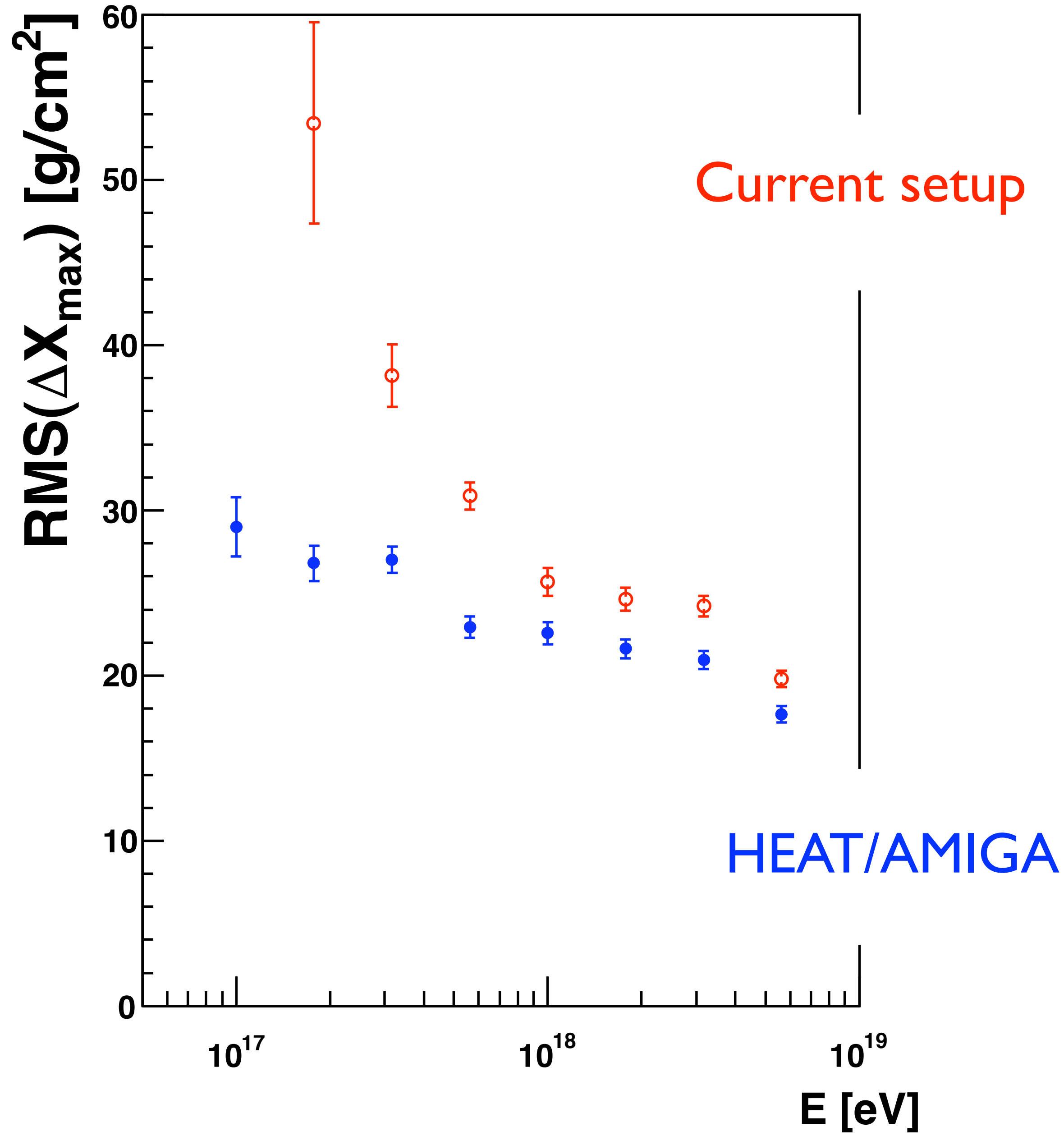


Expected performance (i)

Acceptance strongly selection cut dependent, here shown for high quality cuts (mean X_{max})

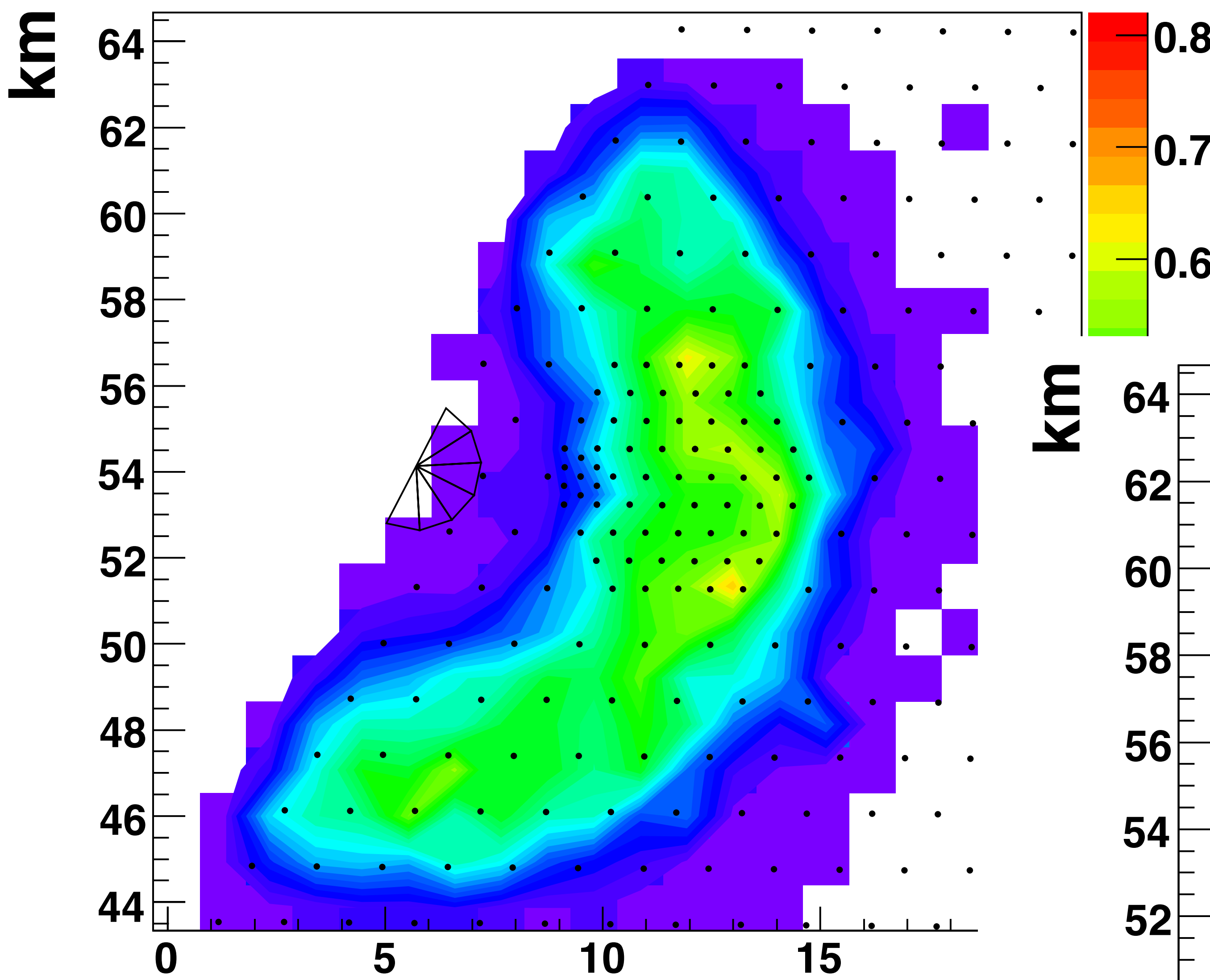
Threshold lowered to ~10^{17} eV





Expected performance (ii)

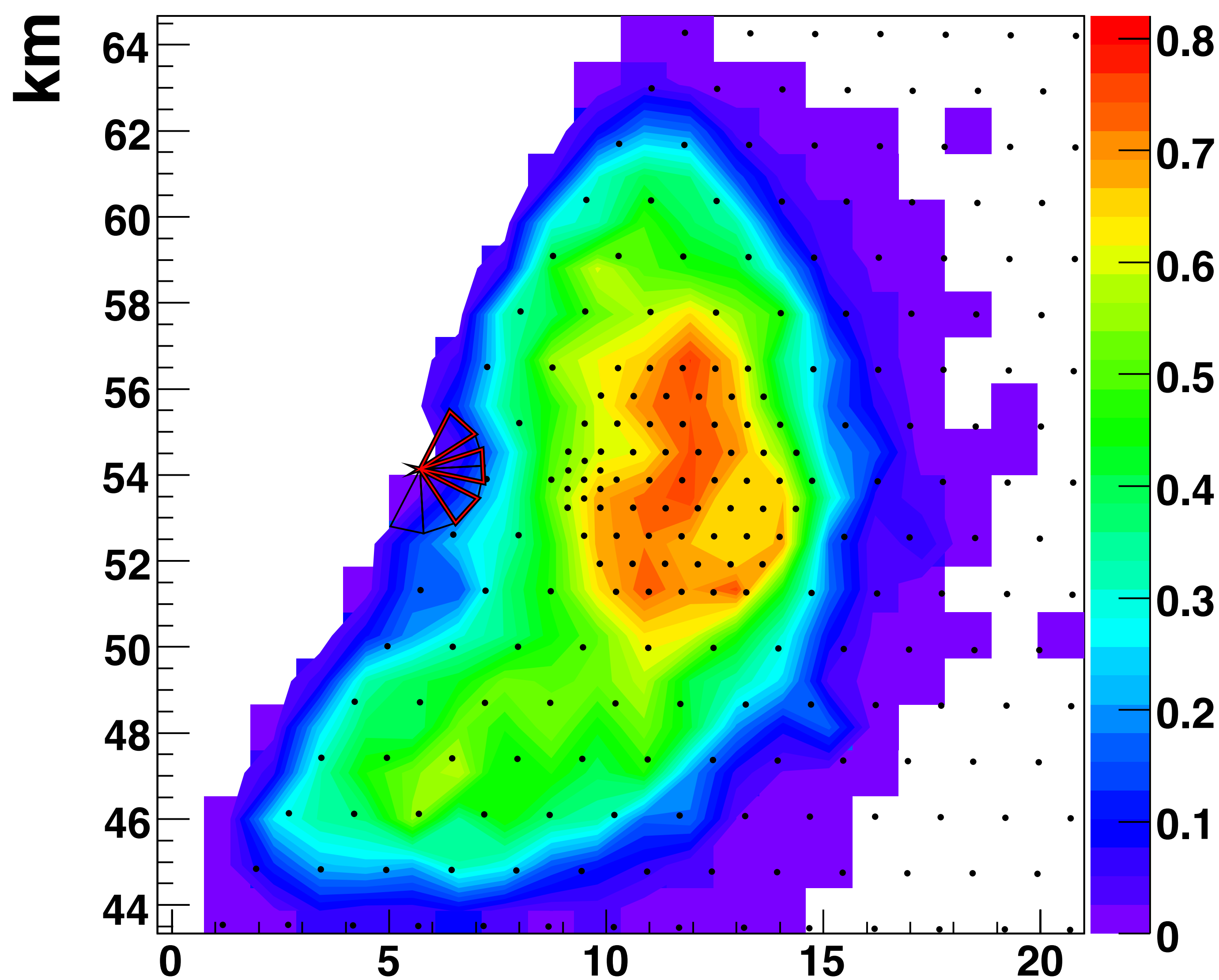
Coihueco telescopes and infill array



Iron showers, $10^{17.5}$ eV

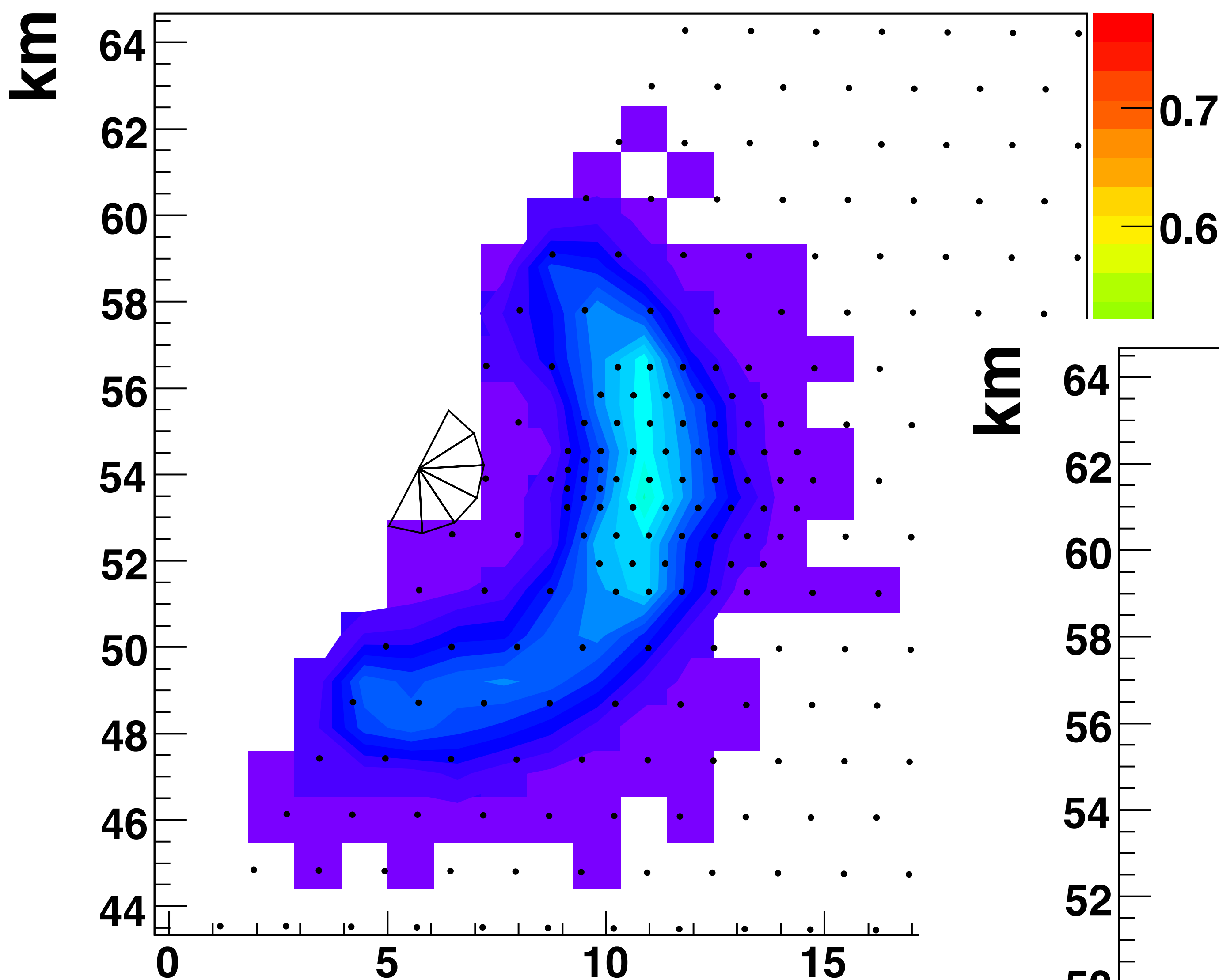
Selection efficiency after quality cuts, hybrid reconstruction

Coihueco+HEAT telescopes and infill array



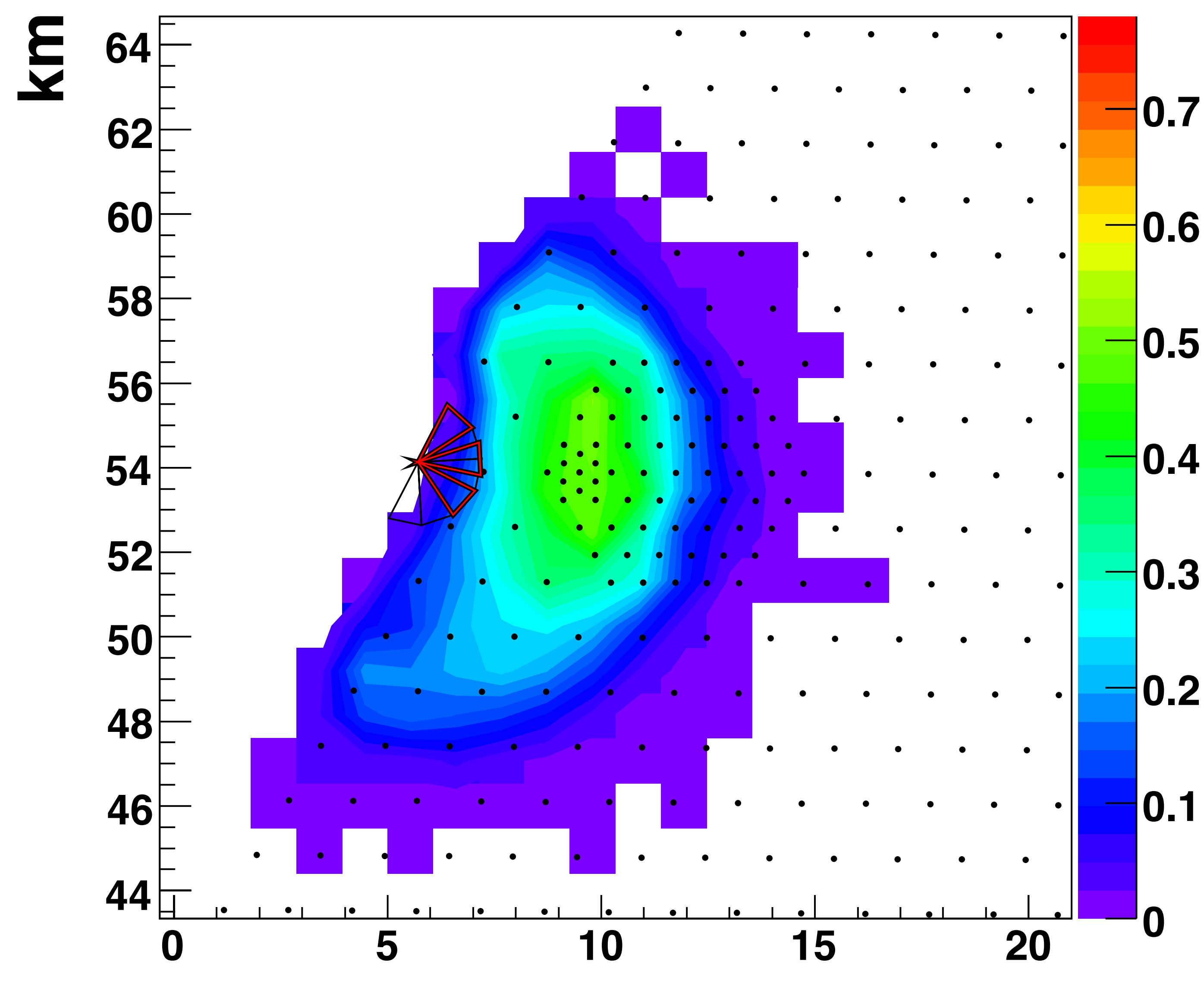
Expected performance (iii)

Coihueco telescopes and infill array



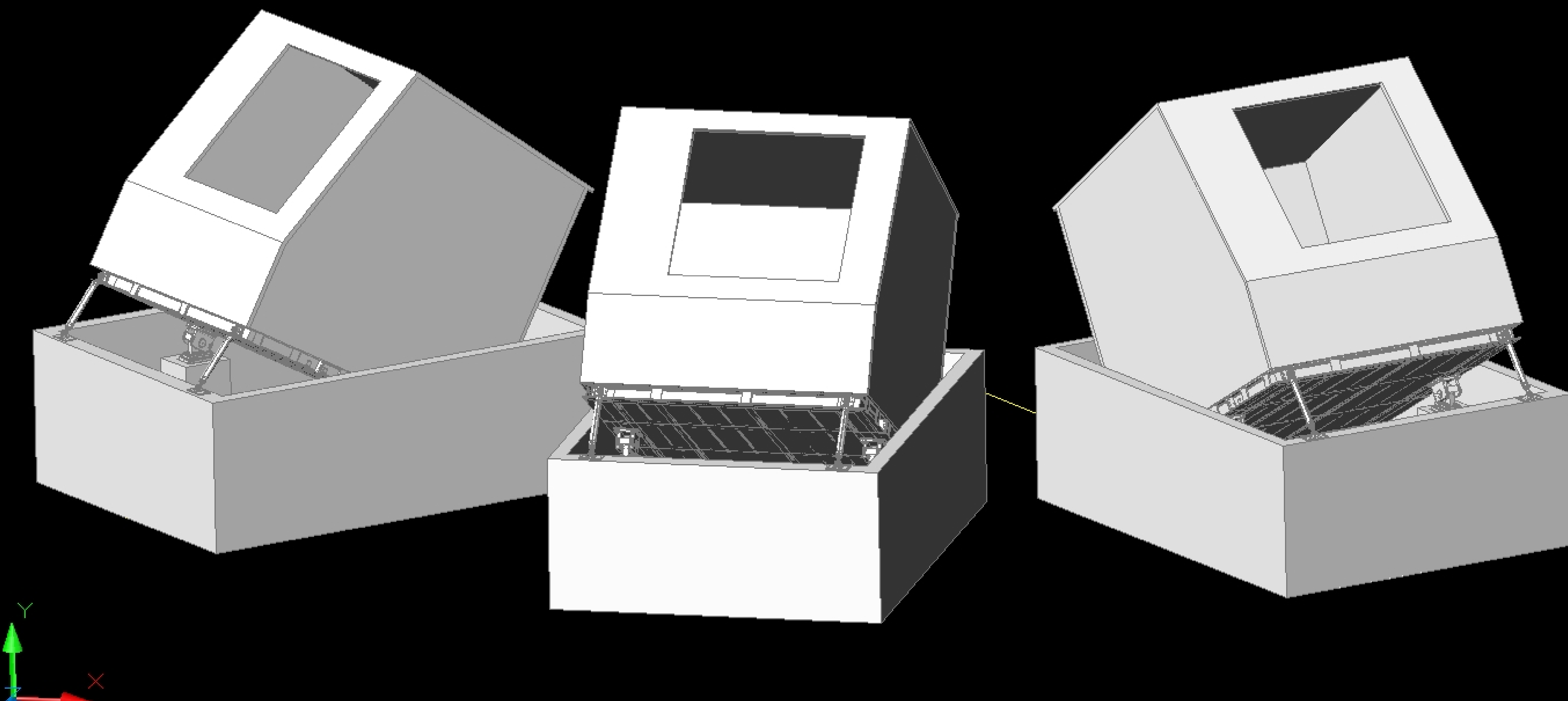
Selection efficiency after quality cuts, hybrid reconstruction

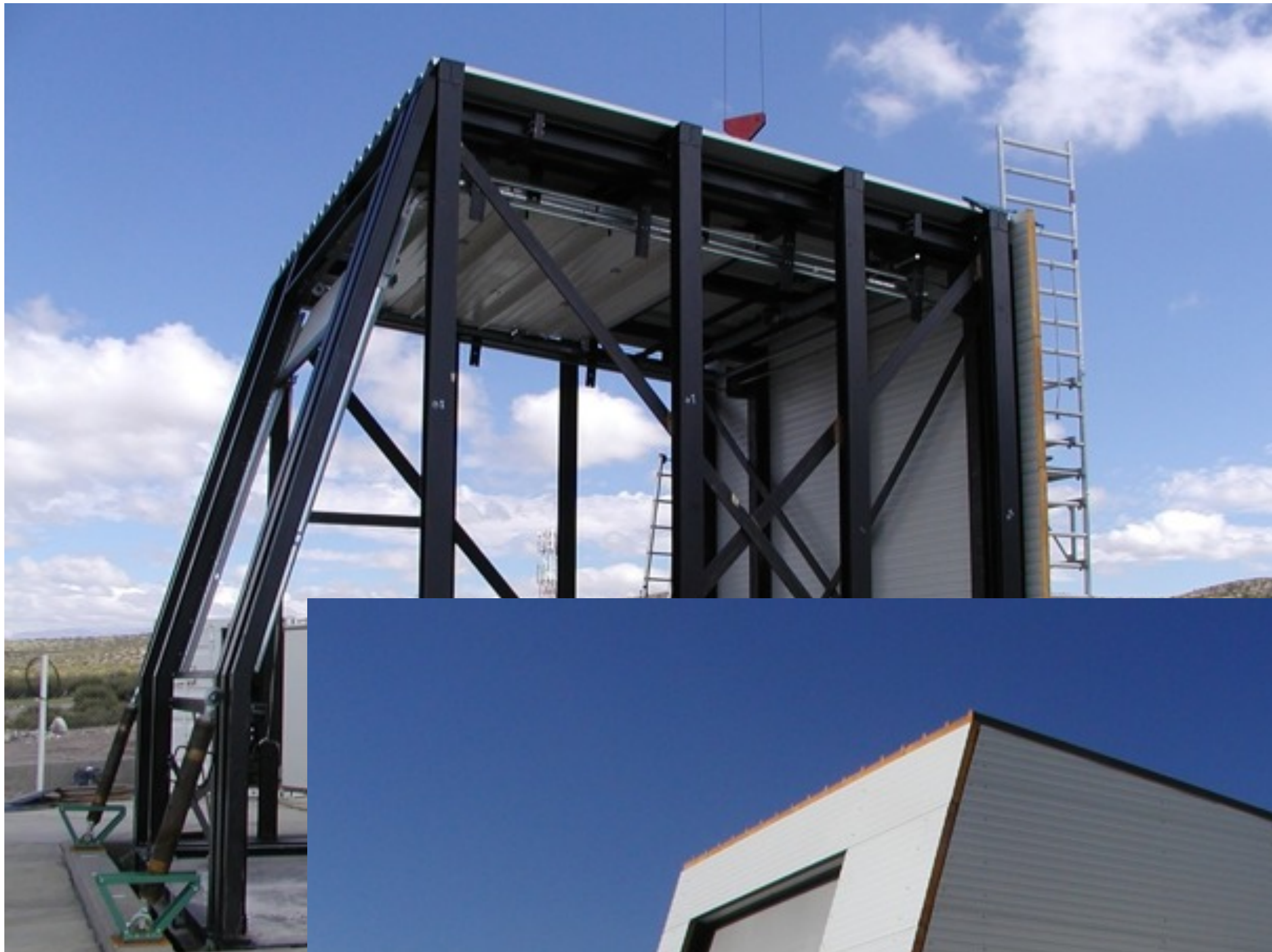
Coihueco+HEAT telescopes and infill array



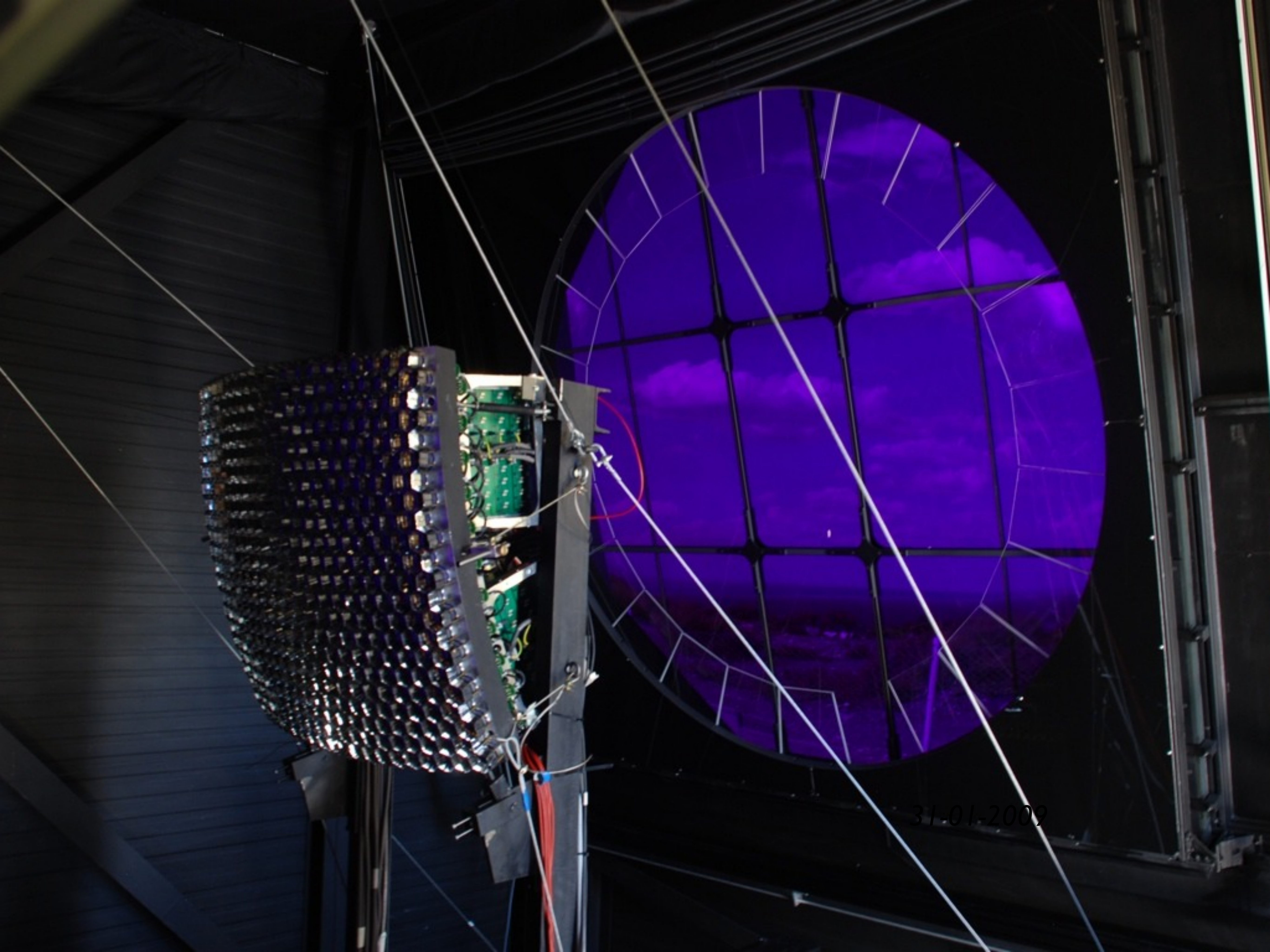
Iron showers, $10^{17.25}$ eV

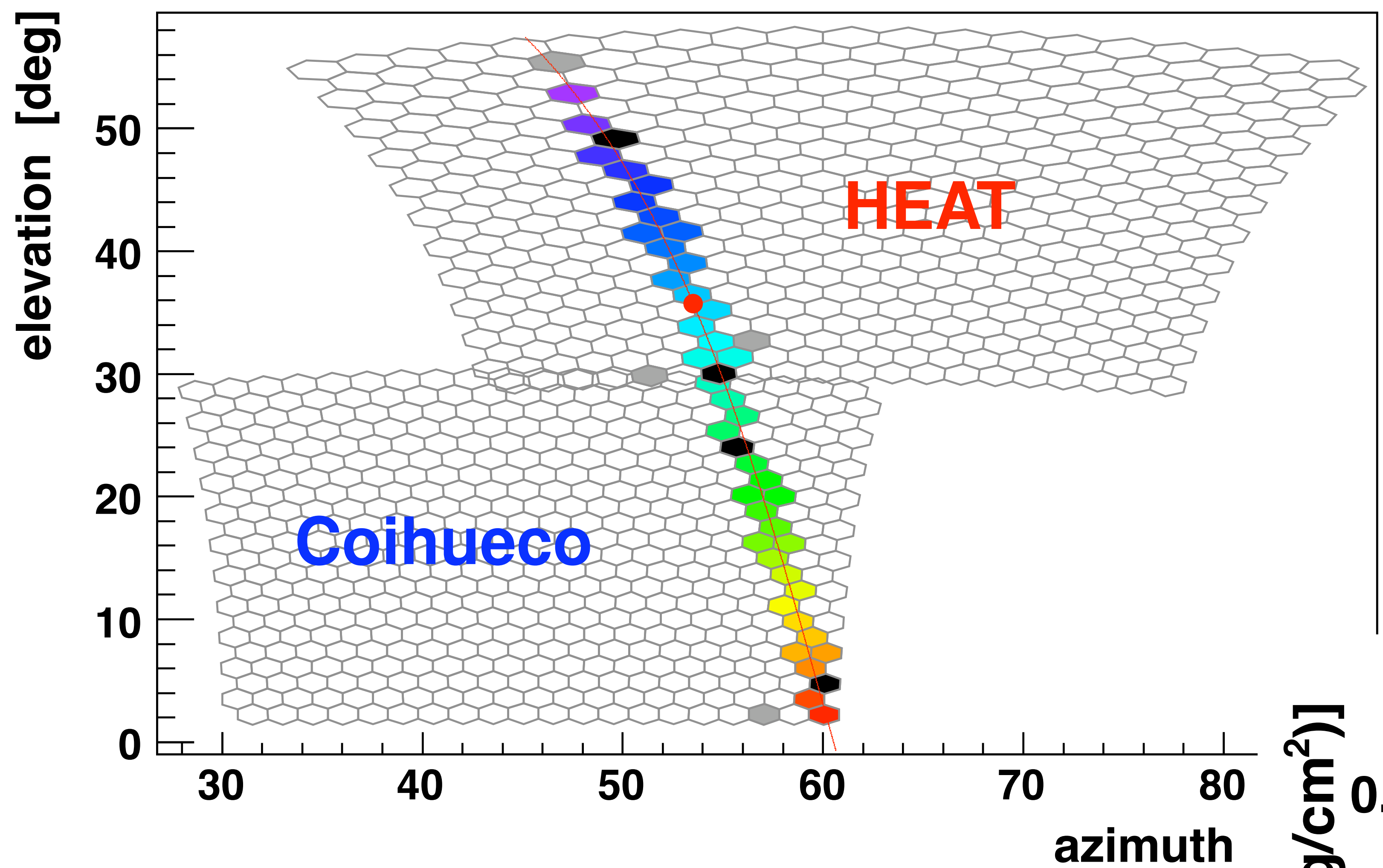
CAD view



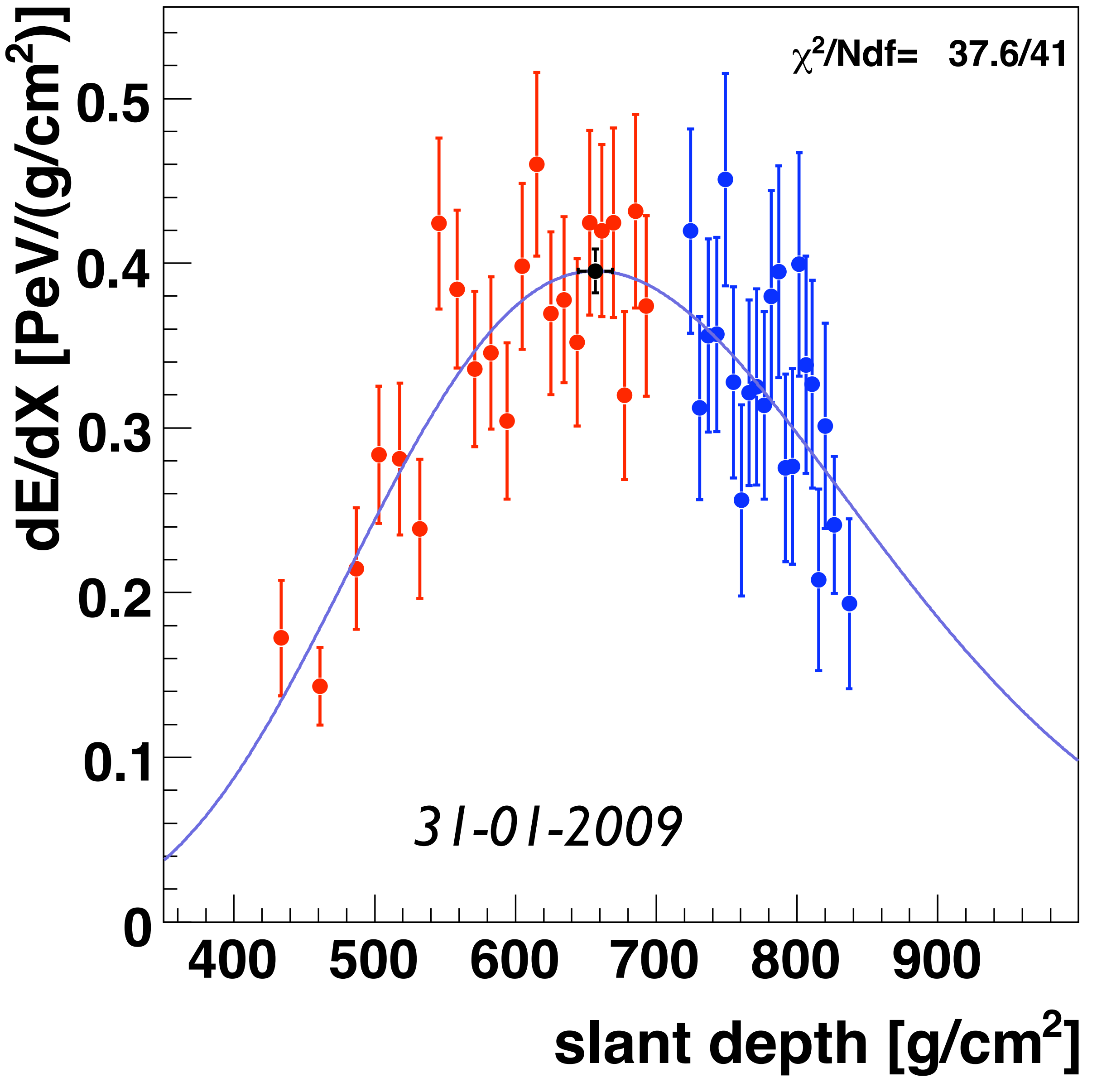





31-01-2009


elevation [deg]
HEAT
Coihueco
azimuth
0
10
20
30
40
50
30
40
50
60
70
80


SDE
SOC


dE/dX [PeV/(g/cm^2)]
χ^2/Ndf= 37.6/41
31-01-2009
slant depth [g/cm^2]
0
0.1
0.2
0.3
0.4
0.5
400
500
600
700
800
900

Event rates and outlook

High-quality events per year

	Energy threshold	Detector array	Hybrid observation
433m infill	$2\ 10^{17}$ eV $5\ 10^{17}$ eV	~13500 ~2500	~1500 ~250
750m infill	$4\ 10^{17}$ eV $3\ 10^{18}$ eV	~12000 ~250	~1200 ~25
1500m	$3\ 10^{18}$eV $1\ 10^{19}$ eV		~500 ~50

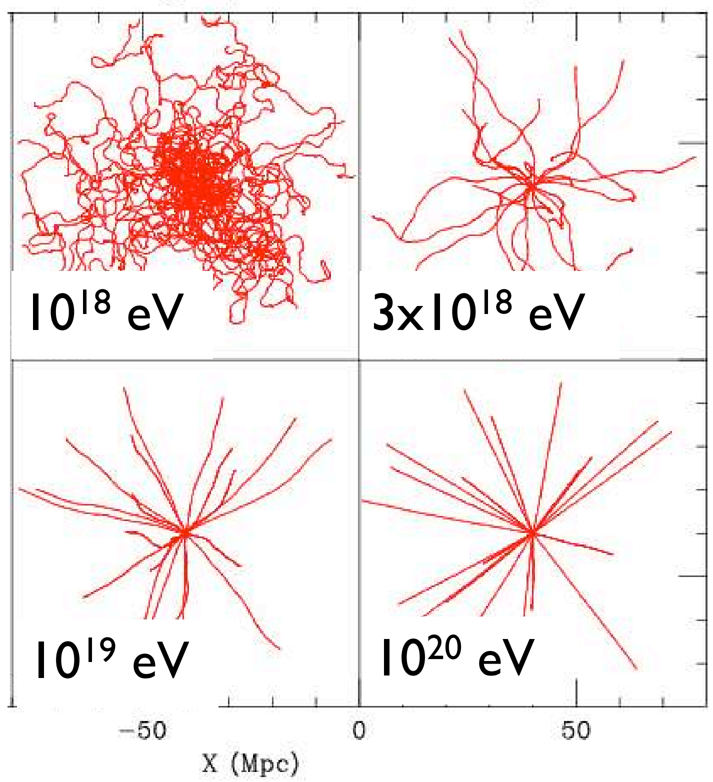
Construction plans

- HEAT first telescope in 2008, other two in 2009
- AMIGA prototype cluster (unitary cell) in 2009/2010
- AMIGA infill tanks 750/433m in 2008/2009
- AMIGA muon counters 750/433m in 2011/2012

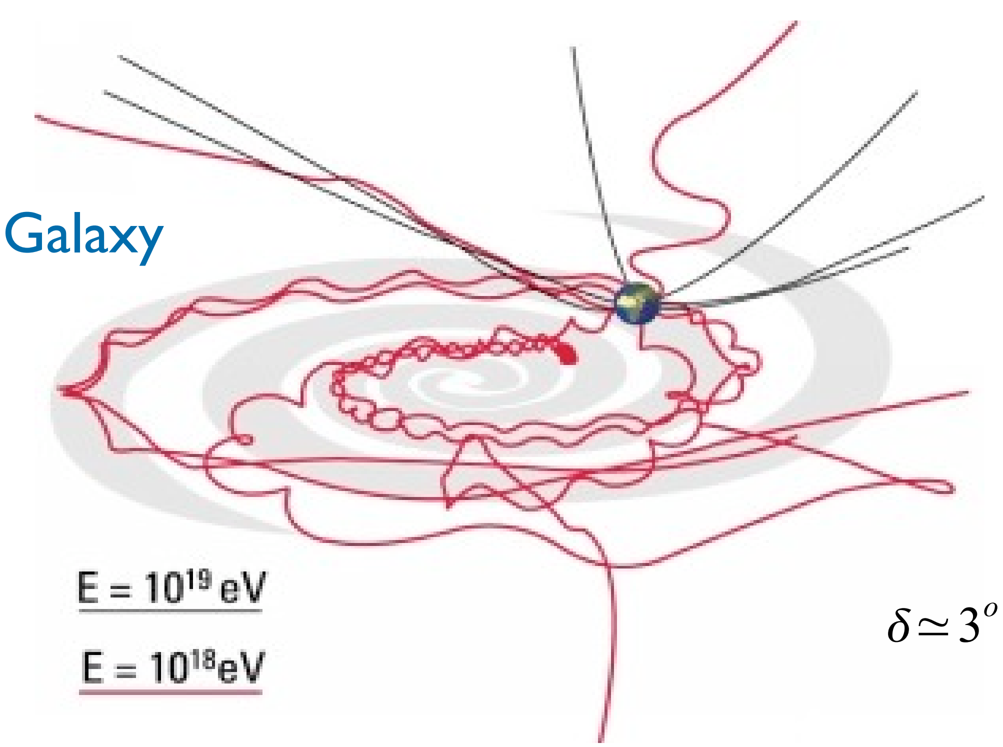
The northern Pierre Auger Observatory

GZK horizon and magnetic field deflection

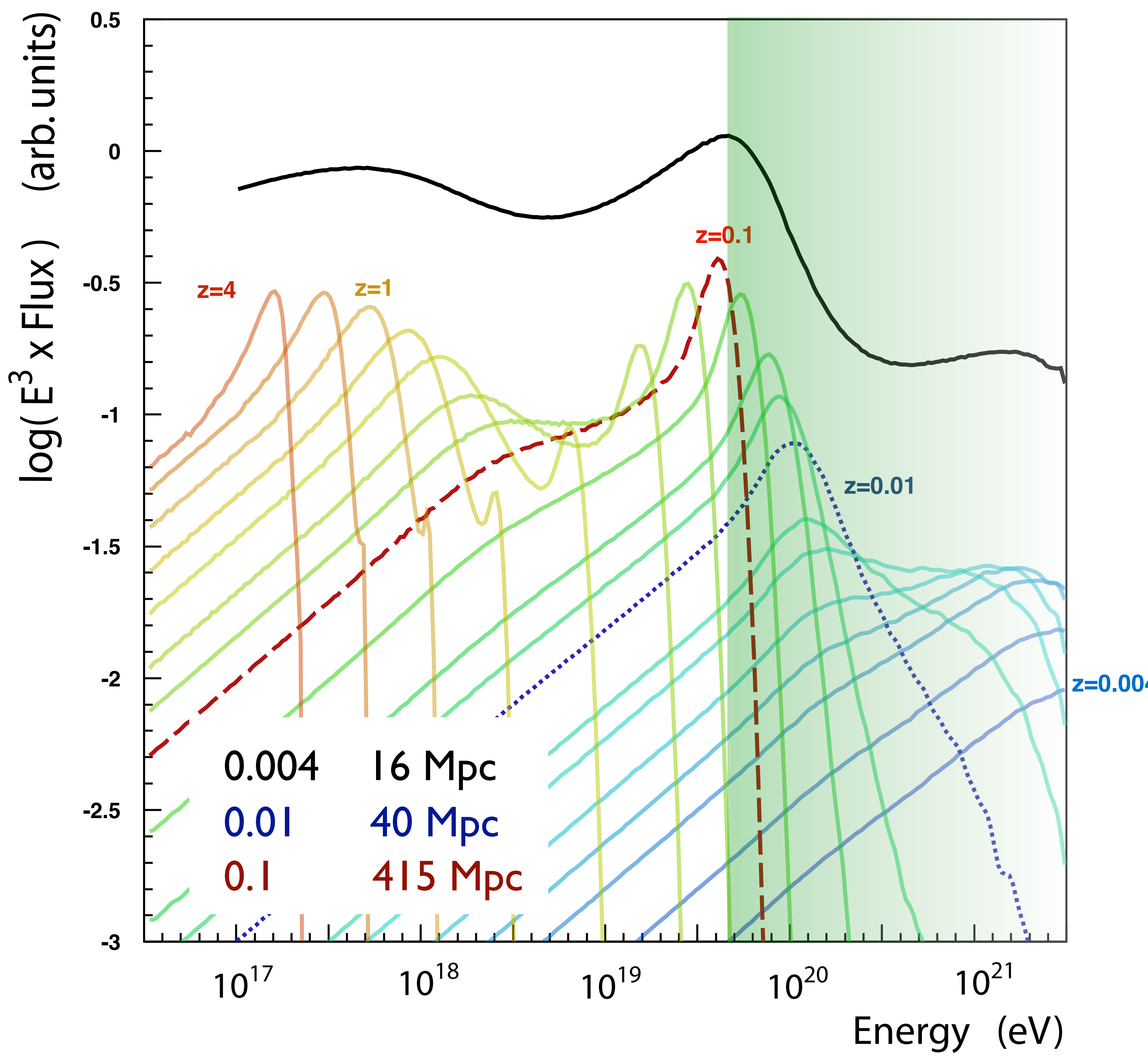
Extragalactic magnetic field



Galaxy



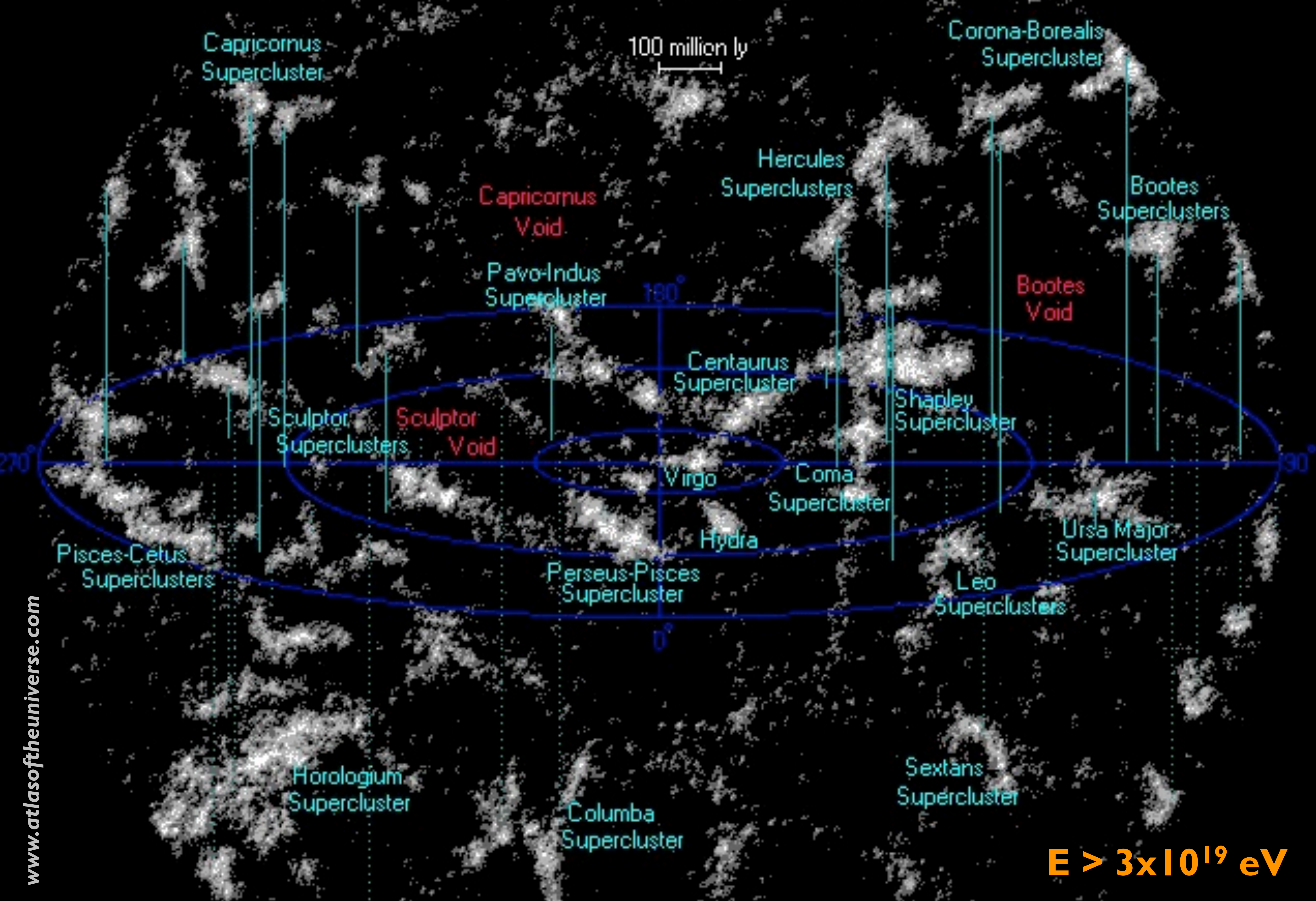
GZK horizon: energy-source relation



$$\delta \simeq 3^o \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times10^{19}\,eV}{E/Z}$$

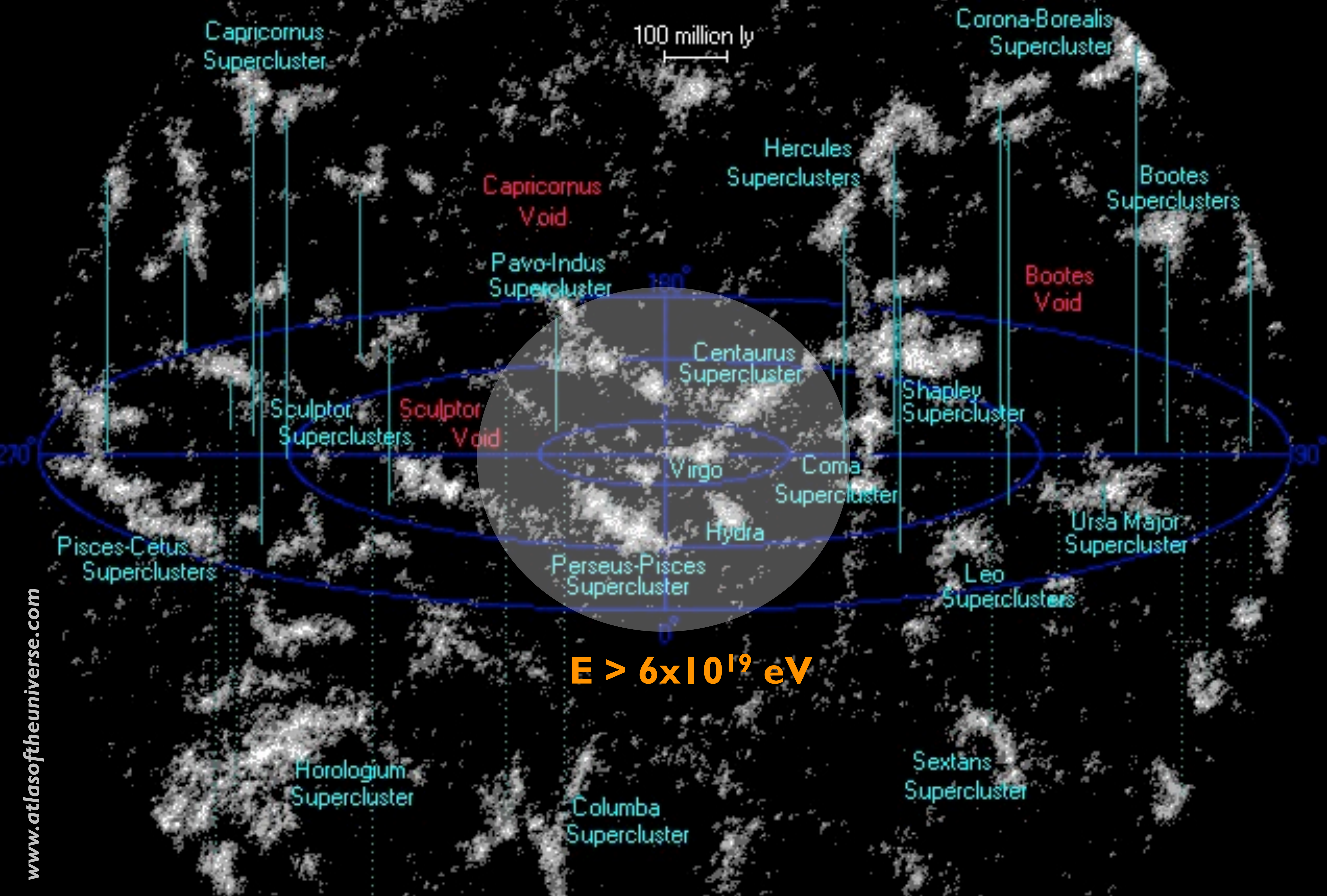
(Bergmann et al., PLB 2006)

Distribution of Galaxies

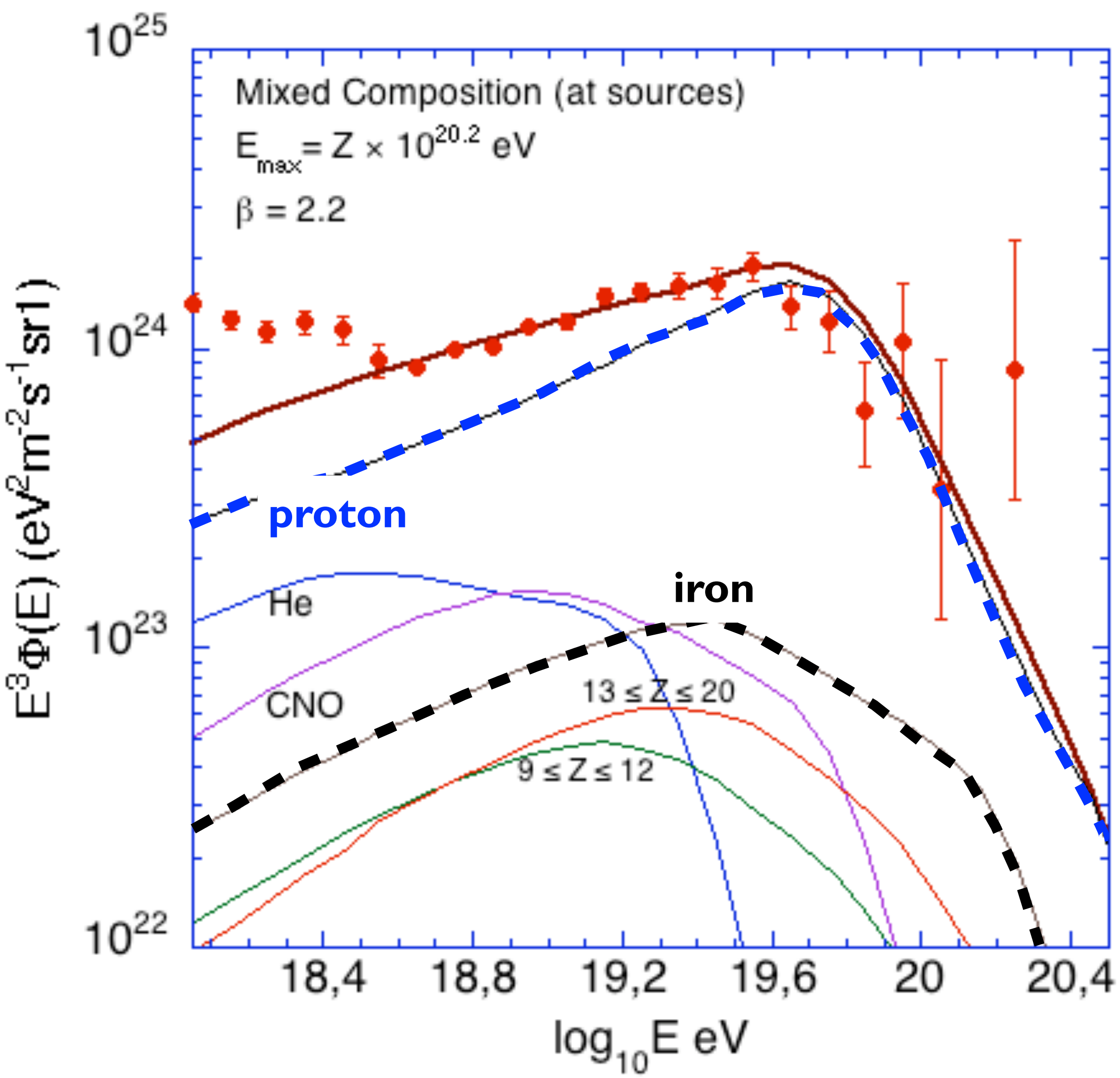


E > 3×10^{19} eV

Distribution of Galaxies



Propagation and max. injection energy

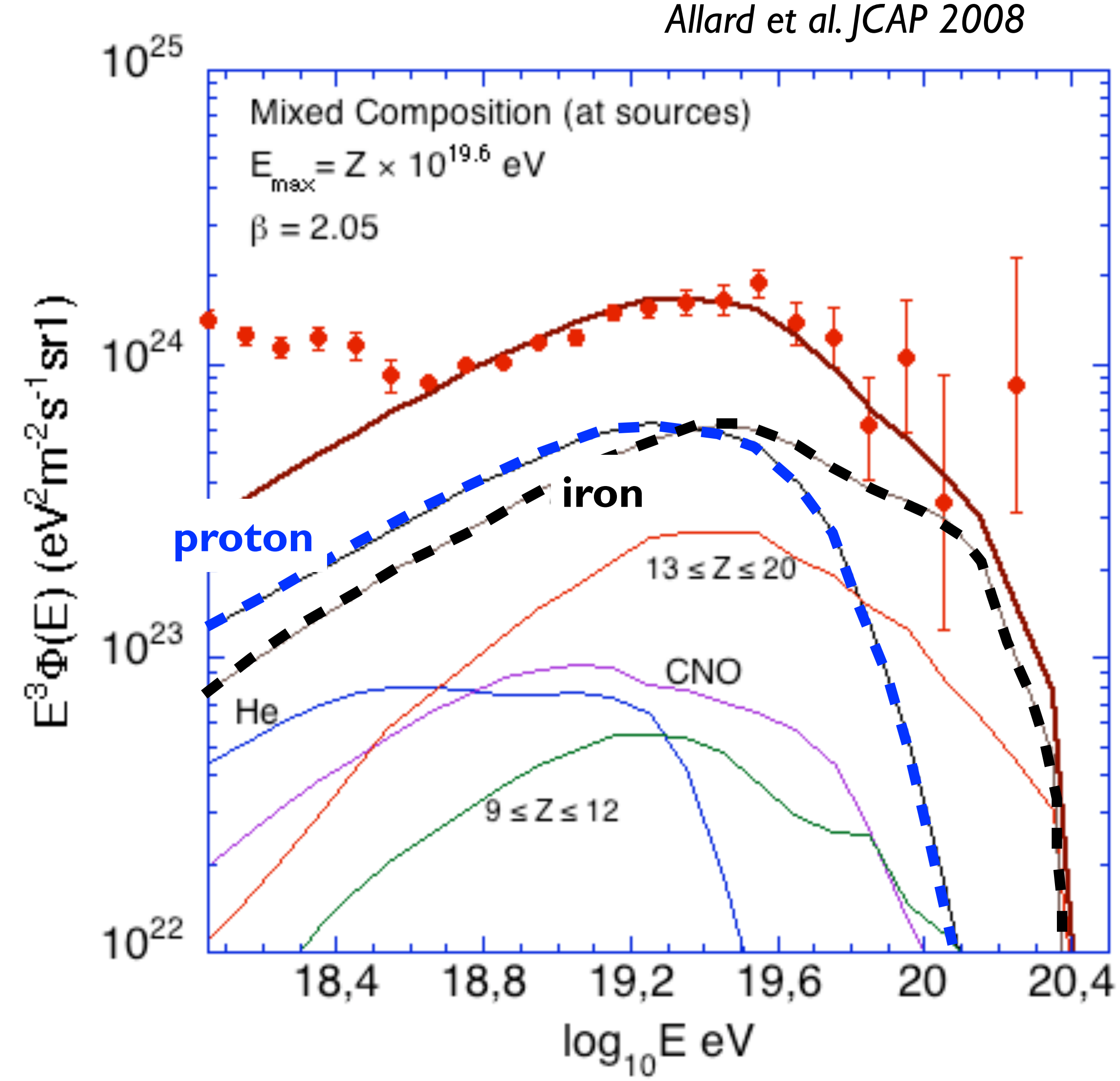


Max. injection energy > 10^{20} eV

Energy loss length

- proton and iron nuclei very similar
- all other nuclei disintegrate very fast

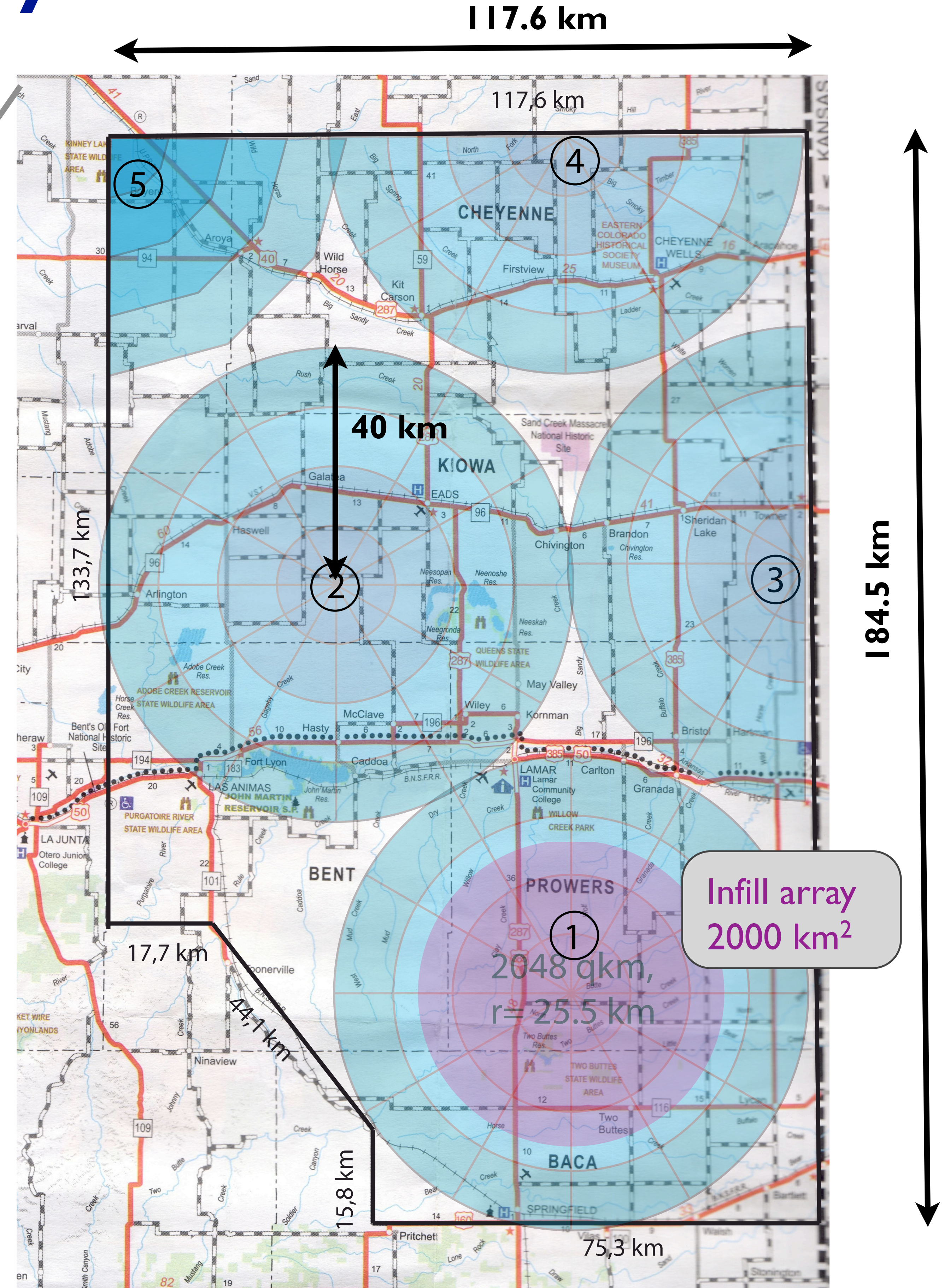
Allard et al. JCAP 2008



Max. injection energy $10^{19.6}$ eV

Auger-North detector layout

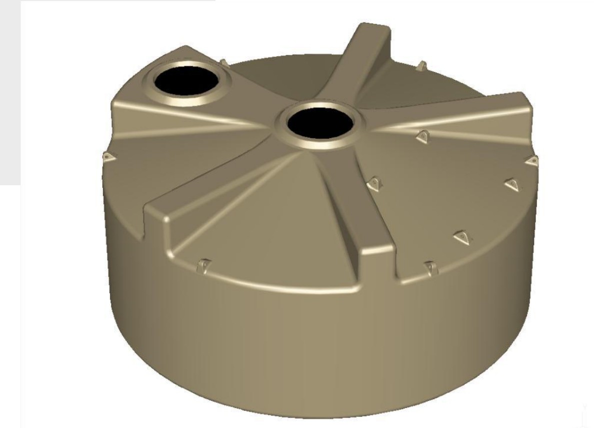
- **Optimized for science and costs**
- **Surface array with 4000 stations:**
  20,000 km^2 with
  $\sqrt{2}$-mile = 2.3 km grid
- **Infill array with 400 stations:**
  2,000 km^2 with
  1-mile = 1.6 km grid
- **39 fluorescence telescopes**

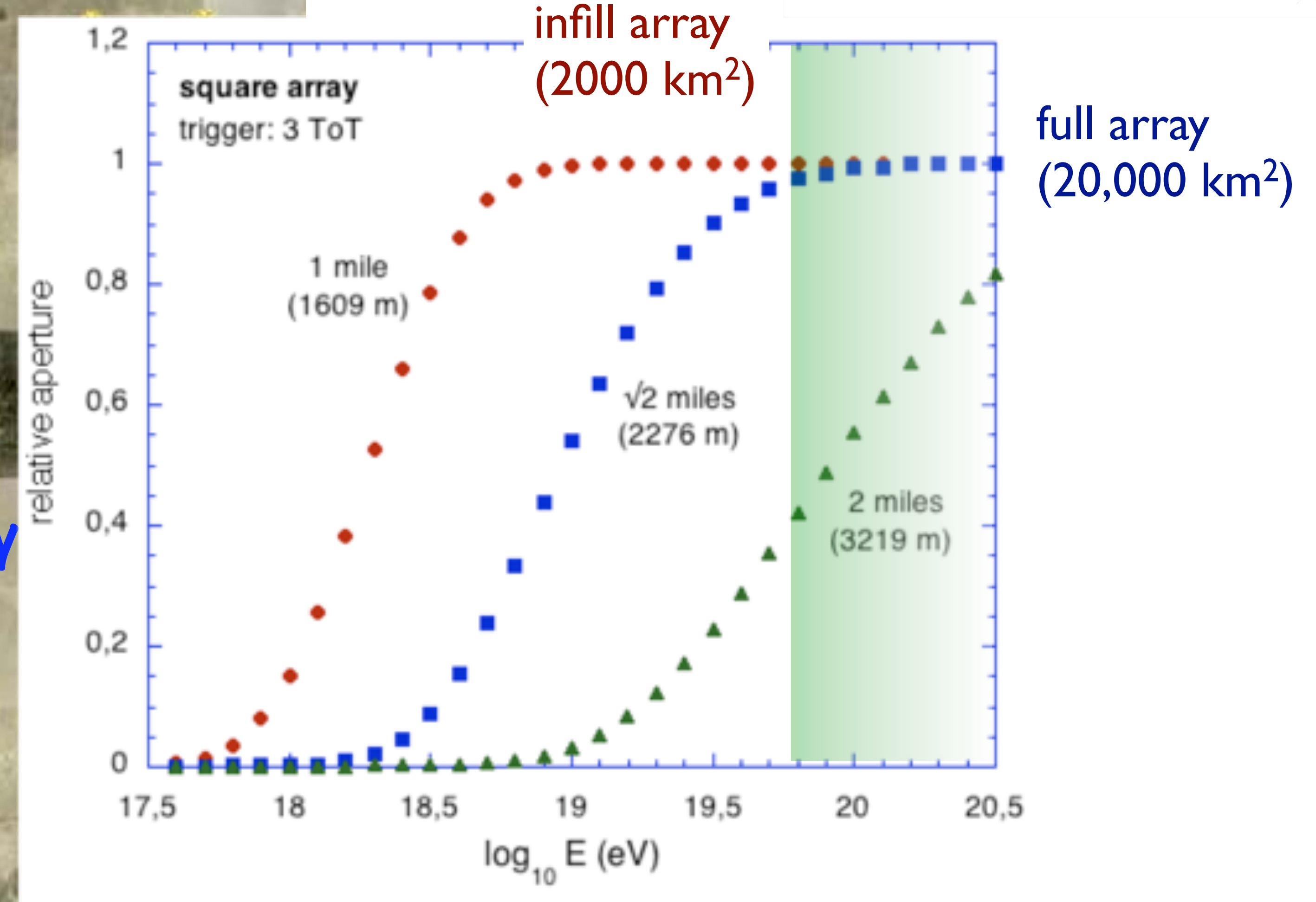


Auger-North detector design (i)

Design optimized for physics aims

- Water-Cherenkov tanks with one PMT only
- Thermally insulated water tanks
- Use of existing 1 mile grid of roads
- Tank-to-tank communication (peer-to-peer network)

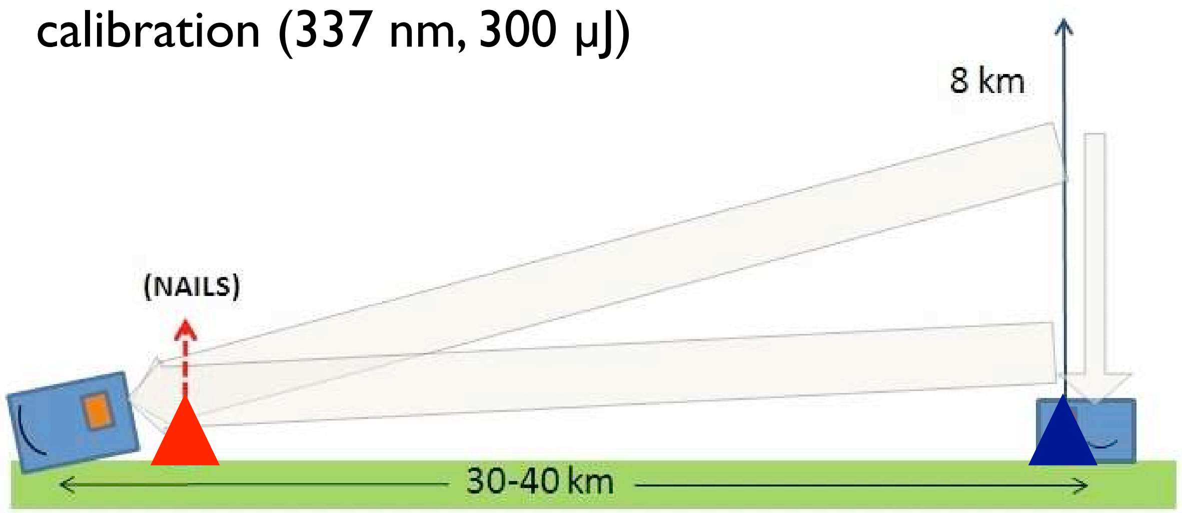




Auger-North detector design (ii)

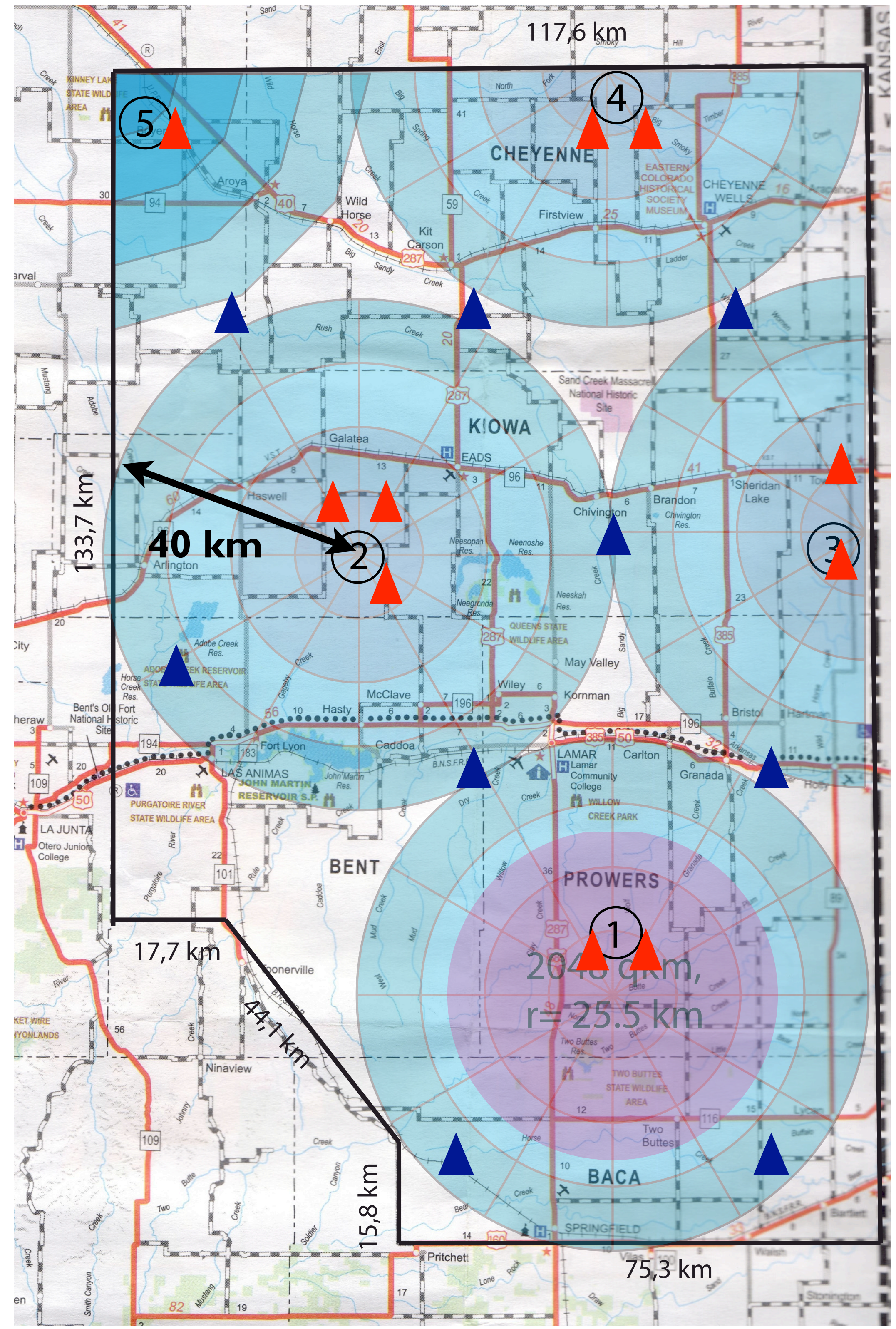
Distant Laser Facility (DLF):
Aerosol measurement
and Raman laser
(355 nm, 7 mJ)

Nitrogen Automated Integrated Laser System (NAILS)
fluorescence telescope
calibration (337 nm, 300 μJ)



AMT
$2m^2$ mirror
2 columns of 16 1 degree pixels
External Trigger from GPS

Raman LIDAR
355 nm Laser
Raman Detector



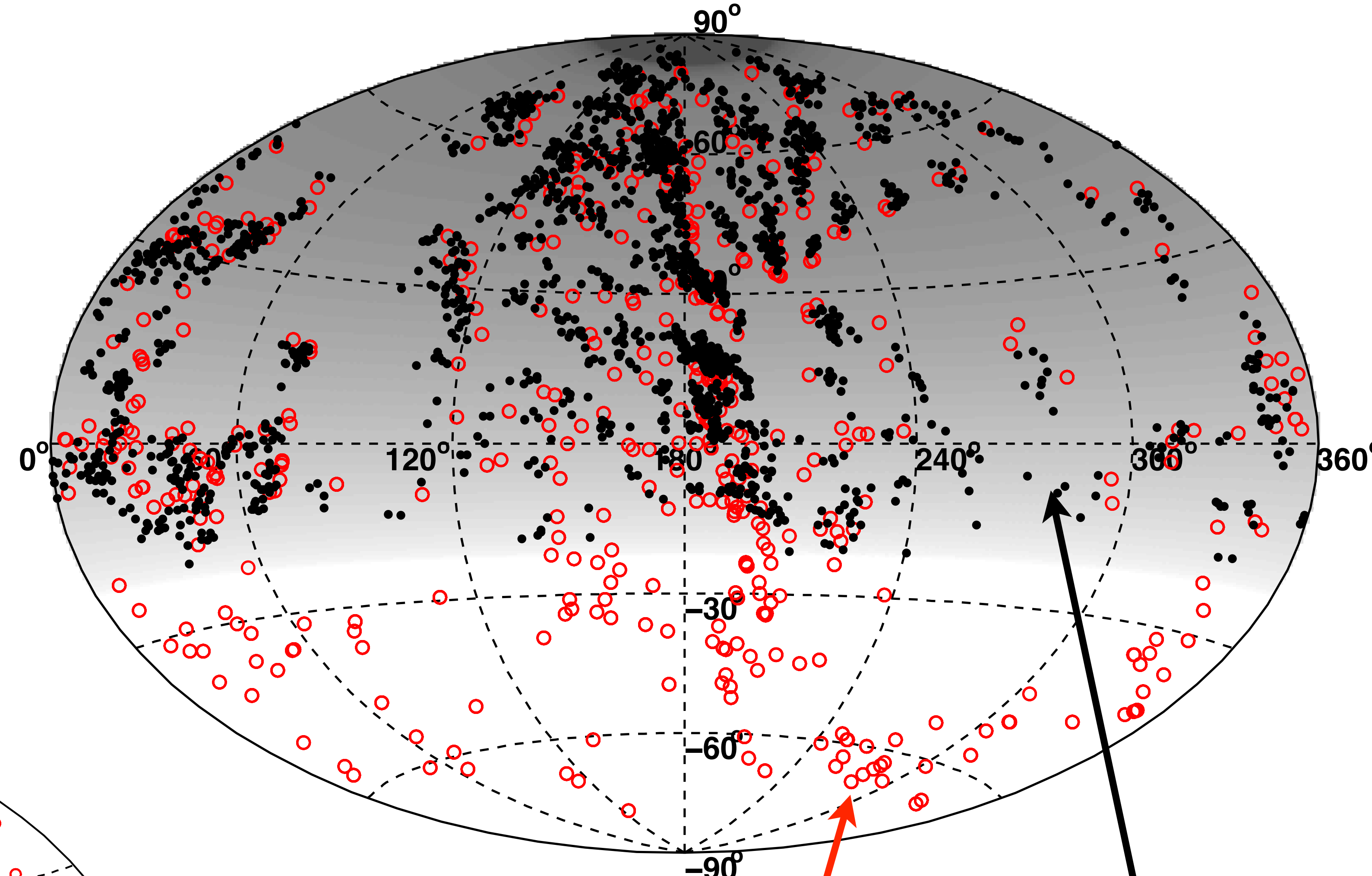
Physics reach: point sources and source regions

South: more than 60 sources
(doublets & AGN correlation)

Auger-South: 300 events
Auger-North: 2100 events

Spectra of sources/source regions

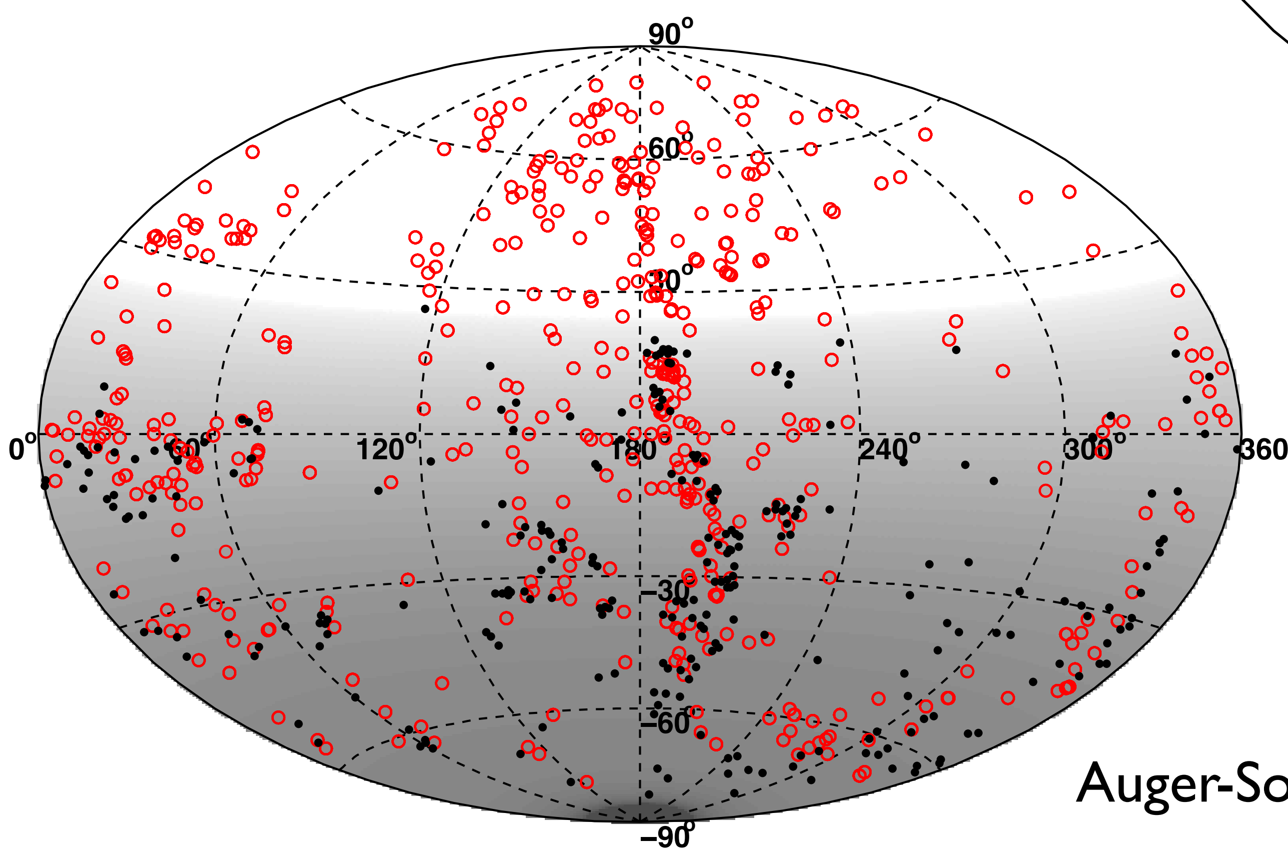
Particle physics at 350 TeV c.m.s.



Auger-North 10yr

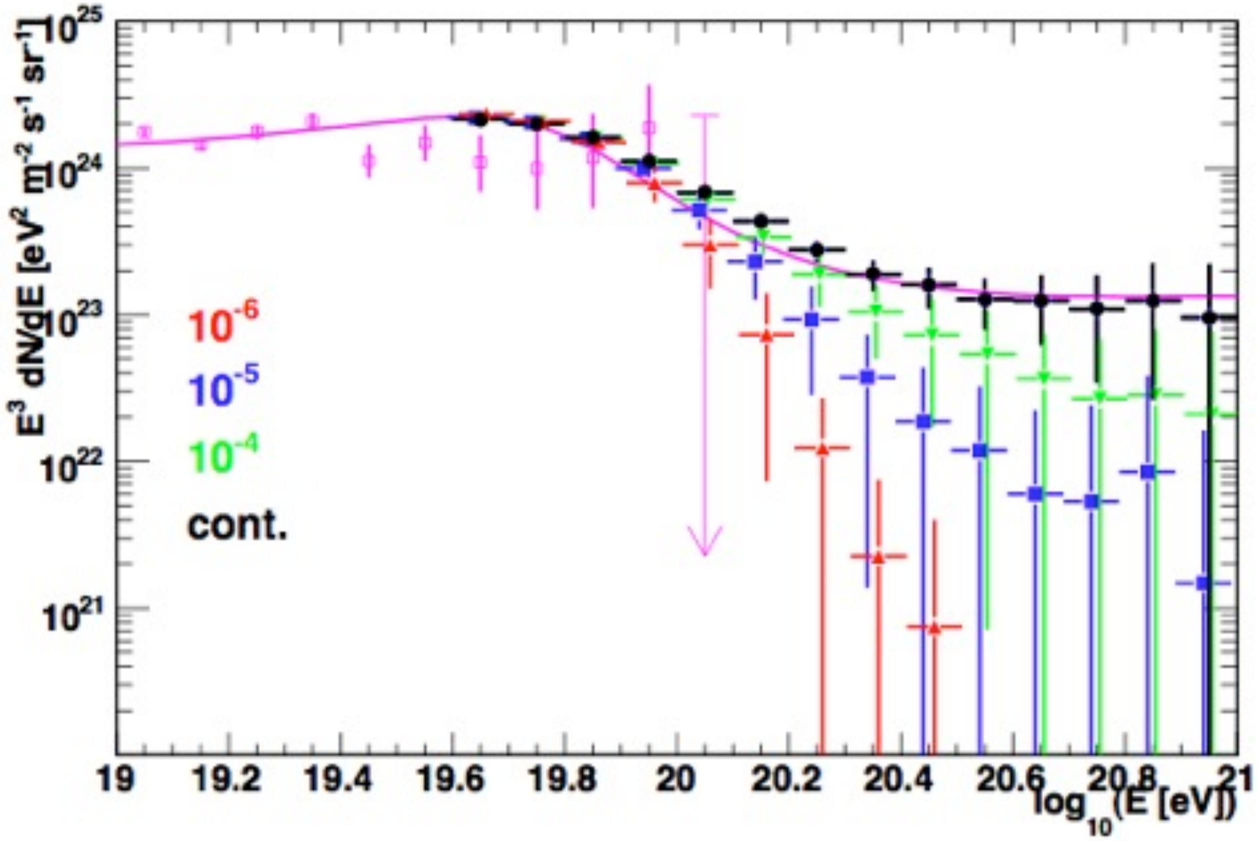
Cosmic rays

AGN within 75 Mpc



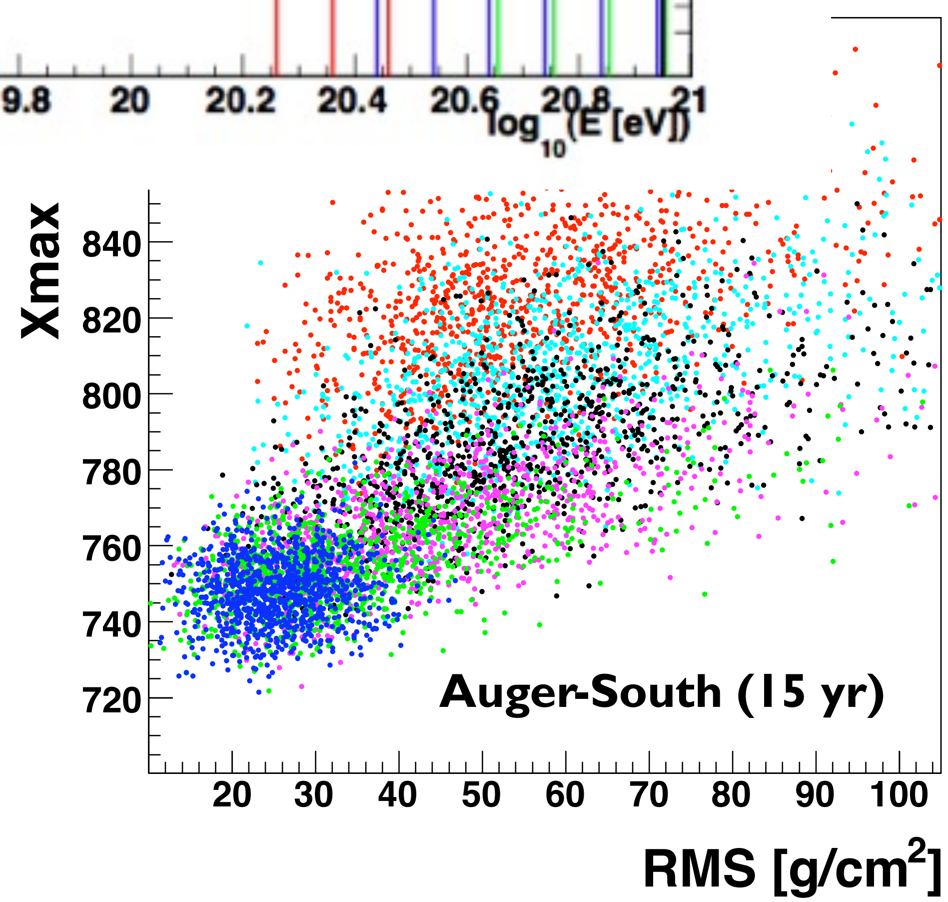
Auger-South 10yr

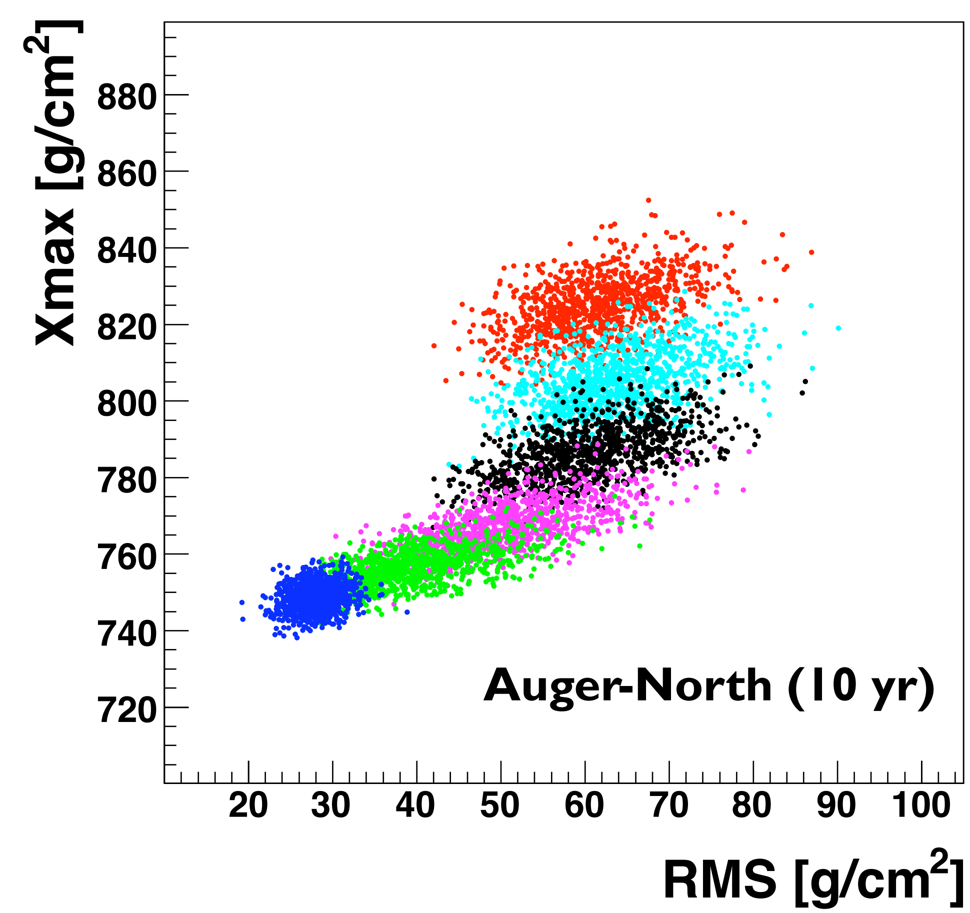
Physics reach: spectrum and composition



Energy spectrum for different source densities (Auger-North, 10 yr)

Composition from mean Xmax and RMS of Xmax

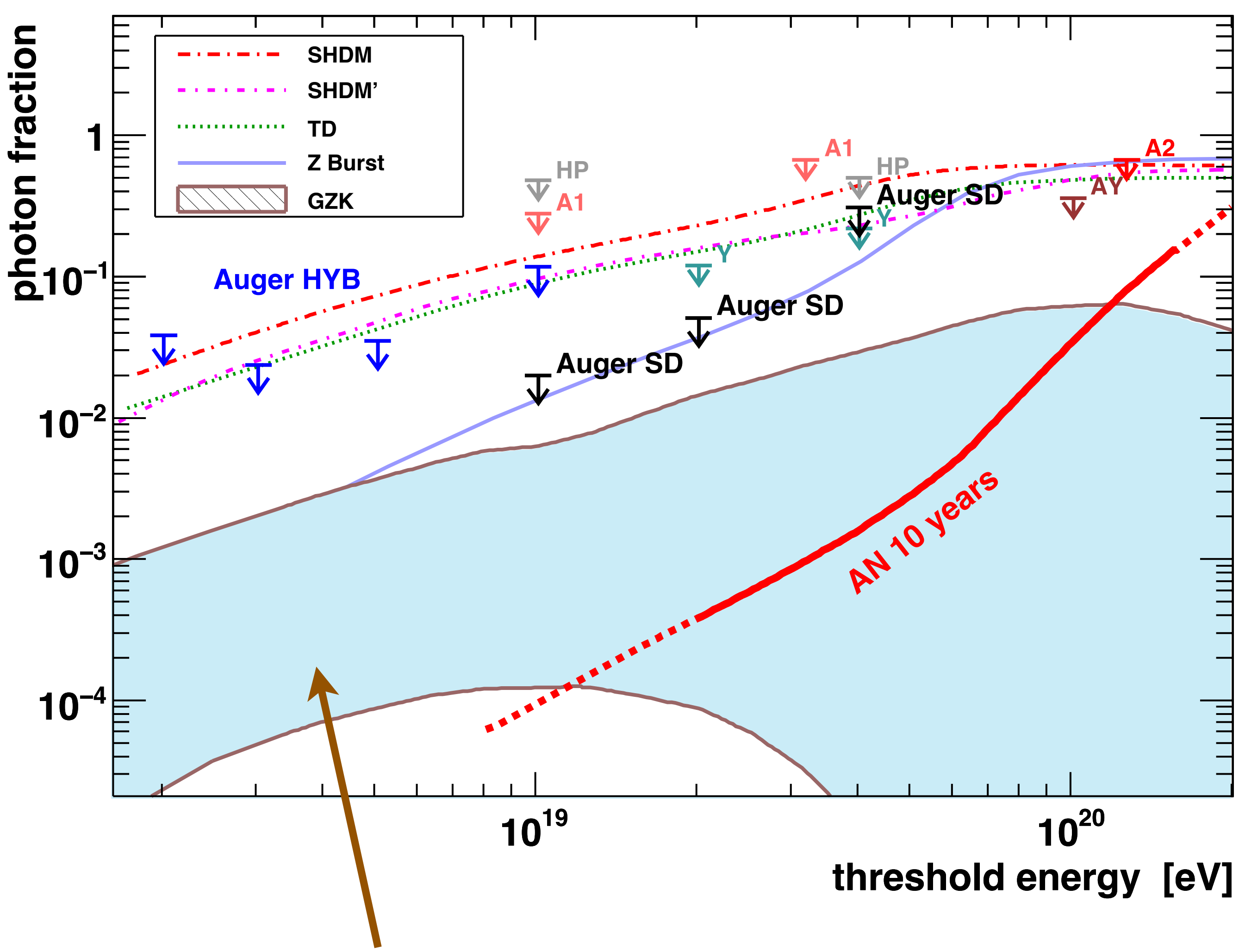




100% proton, 75% proton, 25% iron, 25% proton, 75% iron, 10% proton, 90% iron, 100% iron

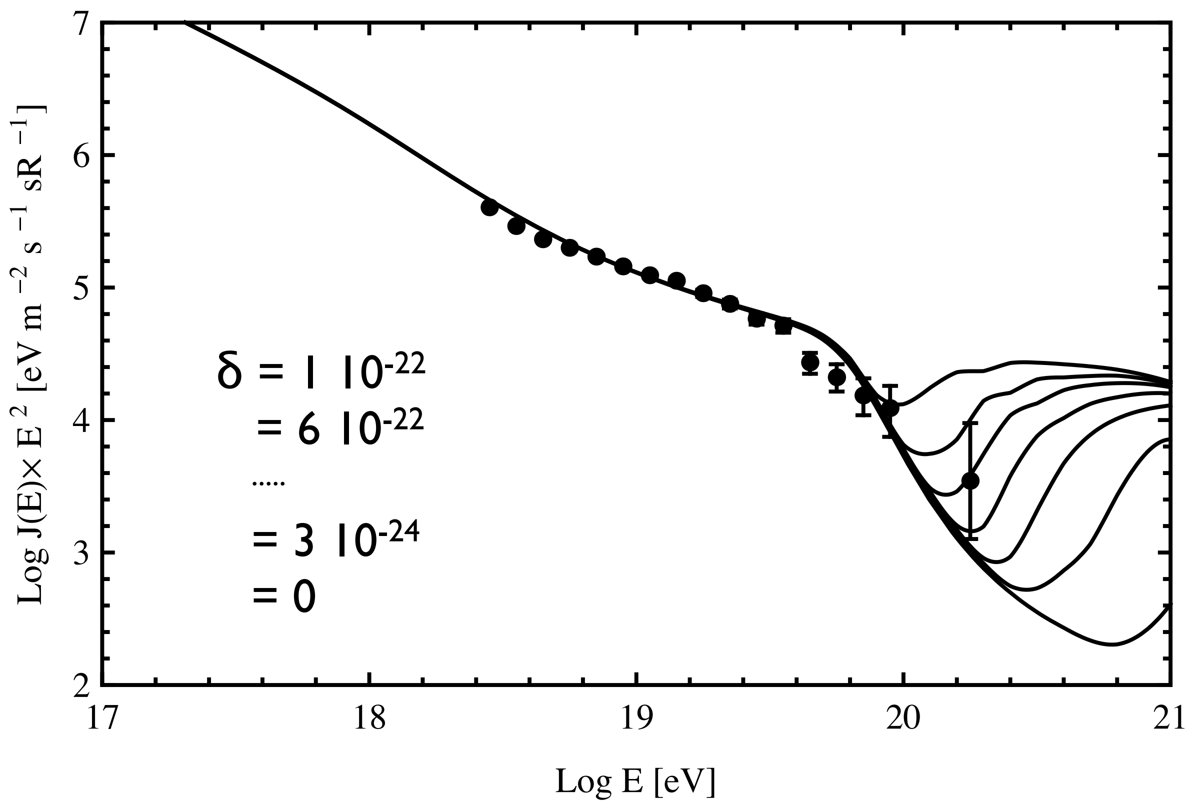
Physics reach: fundamental and particle physics

Photon fraction



Photons from GZK effect
(Gelmini et al., JCAP 2007)

Energy spectrum

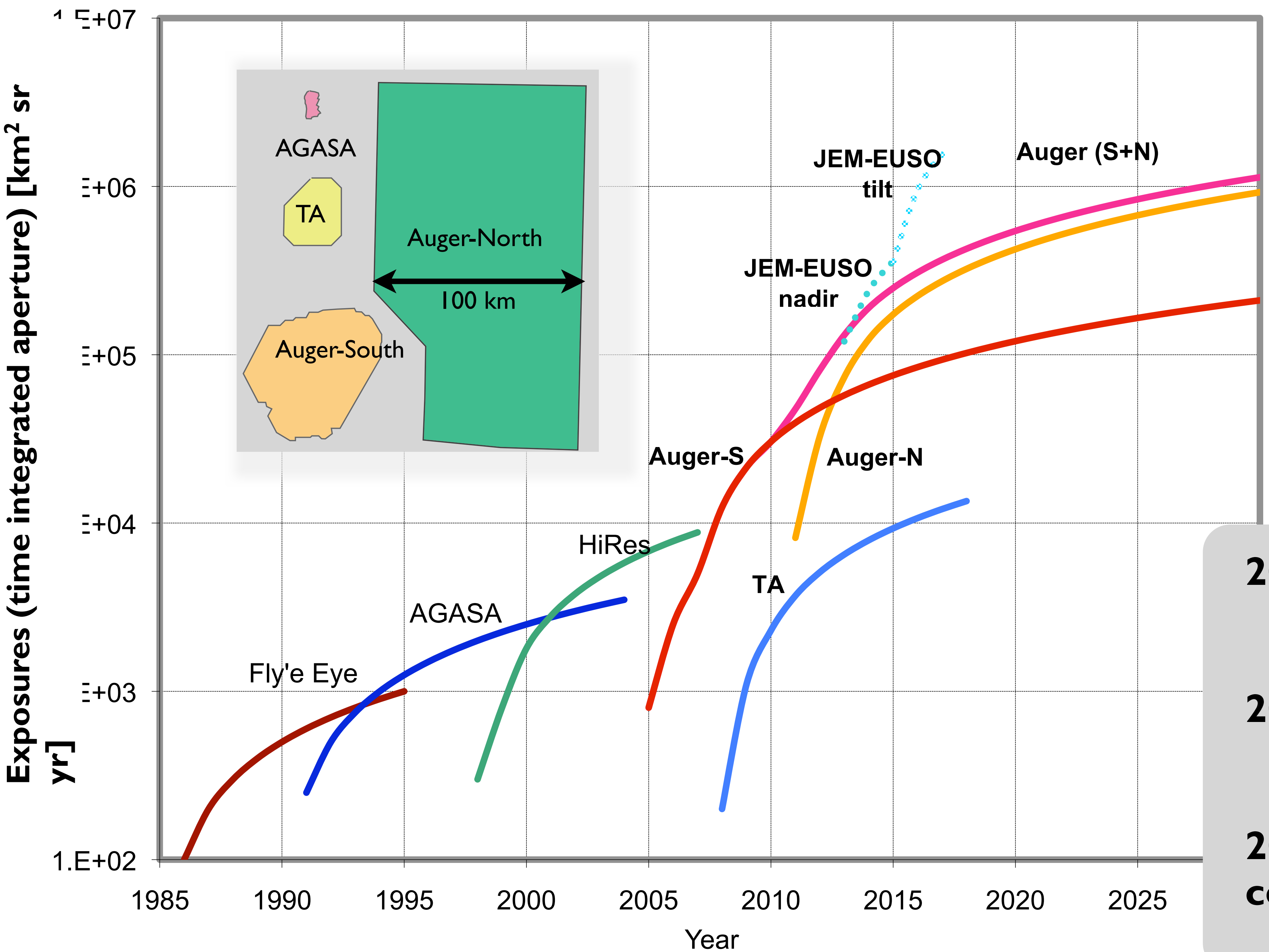


Scully & Stecker, astro-ph 0811.2230

$$4\omega E_\pi = \frac{m^2(2M+m)}{M+m} + 2\delta_{\pi p}E_\pi^2$$

Mono- or bi-elemental composition:
particle physics at 350 TeV CMS with air showers

Current status and timeline



Auger-South: $55M

Auger-North: $120M

2009:
R&D array, funded (10 detector stations)
2009-2011:
Science reviews

2012: Begin of construction (?)

Science with Auger-North

- **The sources of UHECR**
  - Anisotropy ⇉ correlations ⇉ source classes
  - Study individual sources with spectra and composition on the whole sky
- **The acceleration mechanism**
  - Composition evolves from source to here
  - Proton beam !? calibration !
  - $E >> 10^{20}$ eV still difficult; E_{max} ?
- **Propagation and cosmic structure**
  - Map galactic B-field
  - Matter within 100 Mpc
  - Extragalactic B-field small ?
- **Particle physics at 350 TeV**
  - Mass and X_{max}
  - Had. interactions, cross sections ?
  - New physics, Lorentz invariance
- **Multi-messenger astrophysics**
  - Combine the data from photons, neutrinos and charged particles !
  - Sources within field of view of IceCube