Coherent radio pulses from high energy showers: A blooming field

In the memory of a brilliantly original mind

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Particles radiate (or induce radiation Cerenkov)

- Radiation adds coherently for low enough frequencies
- Power of coherent radiation scales with (shower particles)^2
- Showers have lots of particles => Interesting for UHE!

Interference effects give rich diffraction patterns

- Shower could be fully visualized if sufficiently well sampled !!
  (amplitude & phases in every direction)

Signal: contributions from many (all) shower stages

- Reduced fluctuations => good observable

Antennas: cheap

Radio detection: high duty cycle

Main difficulty: dealing with noise

58 J. Jelley 58 extend Cherenkov to radio

61 G. Askary'an excess $Q=\Delta q$

65 In air: high ν

65 J. Jelley 8 "mechanisms" (ICRC65)

- Enhanced Cherenkov (Askary'an)
- Dipole Cherenkov
- Synchrotron radiation
- Transition radiation
- Coulomb field bremsstrahlung
- Induction (by nearby charges)
- Molecular transitions
- Reflections of continuous waves (Doppler shifted)

Complex some are limiting cases of given situations **but it is all in Maxwell's laws!**

67-70 Air: e^+e^- separation in B_{Geo} dominant (Th & exp)

75 decline of field, steep ldf, storm interference …

90 ν detection: full calculations in ice (ZHS)

New initiatives radio telescopes, air showers, ice, salt …

00 Lab measurements

Air showers 1st generation LOPES, CODALEMA, ANITA (GHz)

10 Full simulations (ZHS algorithm + MC)

2nd generation LOFAR, AERA, Tunka-Rex (E, X_{max})

20 Ambitious plans: GRAND, AugerRadio, phased arrays …

Calculations are key: Based on simple solution

Maxwell's Equations in transverse gauge

$$\nabla^2 \phi = -\frac{\rho}{\epsilon}$$

$$\nabla^2 \mathbf{A} - \mu\epsilon \frac{\partial^2 \mathbf{A}}{\partial^2 t} = -\mu \mathbf{J}_\perp$$

The transverse current is the divergenceless component (the transverse projection at large distances)

$$J_\perp = \hat{\mathbf{u}} \times (\hat{\mathbf{u}} \times \mathbf{J})$$

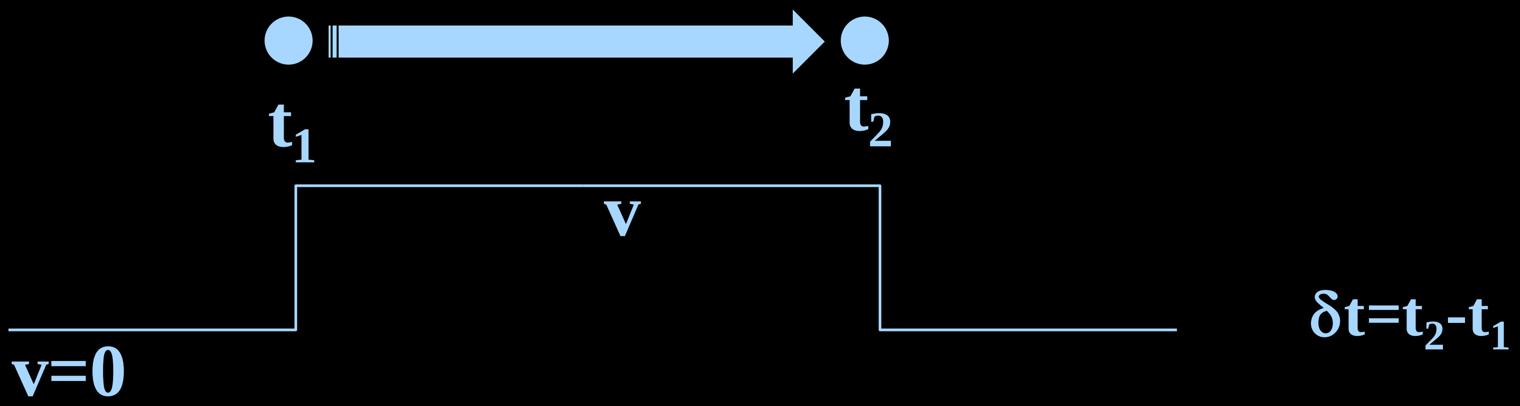
Well known solution, Vector potential A gives us the radiated field

$$\phi = \frac{1}{4\pi\epsilon} \int \frac{\rho(\mathbf{x}', t')}{|\mathbf{x} - \mathbf{x}'|} d^3\mathbf{x}'$$

$$\mathbf{A} = \frac{\mu}{4\pi} \int \frac{\mathbf{J}_\perp(\mathbf{x}', t')}{|\mathbf{x} - \mathbf{x}'|} \delta\left(\sqrt{\mu\epsilon}|\mathbf{x} - \mathbf{x}'| - (t - t')\right) d^3\mathbf{x}' dt'$$

Delta of **Retarded time** with $\sqrt{\mu\varepsilon} = \mathrm{n}c$

Solve for simple case (constant speed)

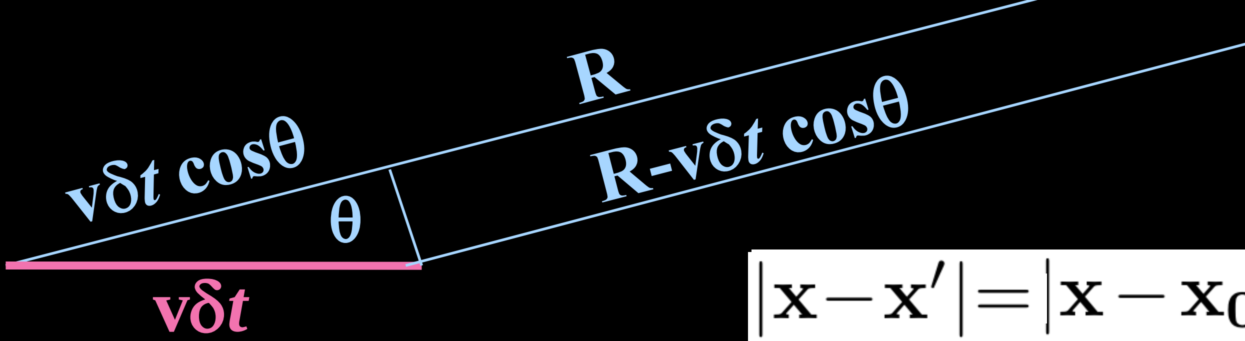


position $\mathbf{x}_0 - \mathbf{v}t'$

$$\mathbf{J}_\perp(\mathbf{x}', t') = e\mathbf{v}_\perp \delta^3\left(\mathbf{x}' - \mathbf{x_0} - \mathbf{v}t'\right)\left[\Theta(t' - t_1) - \Theta(t' - t_2)\right]$$

Organize *t* and *t'* and massage

$$\delta\left(\sqrt{\mu\epsilon}|\mathbf{x}-\mathbf{x}'|-(t-t')\right)$$



Fraunhofer approximation

i.e. $R = |\mathbf{x}-\mathbf{x_0}|$

$$|\mathbf{x}-\mathbf{x}'| = |\mathbf{x}-\mathbf{x_0}-\mathbf{v}t'| \simeq R-\mathbf{v}\cdot\hat{\mathbf{u}}t'$$

$$\delta\left(t'(1-n\beta\cos\theta)-\left(t-\frac{nR}{c}\right)\right)$$

$$\frac{1}{|1-n\beta\cos\theta|}\delta\left(t'-\frac{t-\frac{nR}{c}}{1-n\beta\cos\theta}\right)$$

Substitute into solution for A

$$RA(t,\theta) = \frac{e\mu_r}{4\pi\epsilon_0 c^2}\mathbf{v}_\perp \delta t$$

$$\frac{\Theta\left(t - \frac{nR}{c} - (1 - n\beta\cos\theta)t_1\right) - \Theta\left(t - \frac{nR}{c} - (1 - n\beta\cos\theta)t_2\right)}{(1 - n\beta\cos\theta)\delta t}$$

$$\theta \longrightarrow \theta_C$$

Divergence at Cherenkov angle? **NO!!**

We formally get derivative of Theta funciton

Limit $(1 - n\beta\cos\theta)\delta t \rightarrow 0$

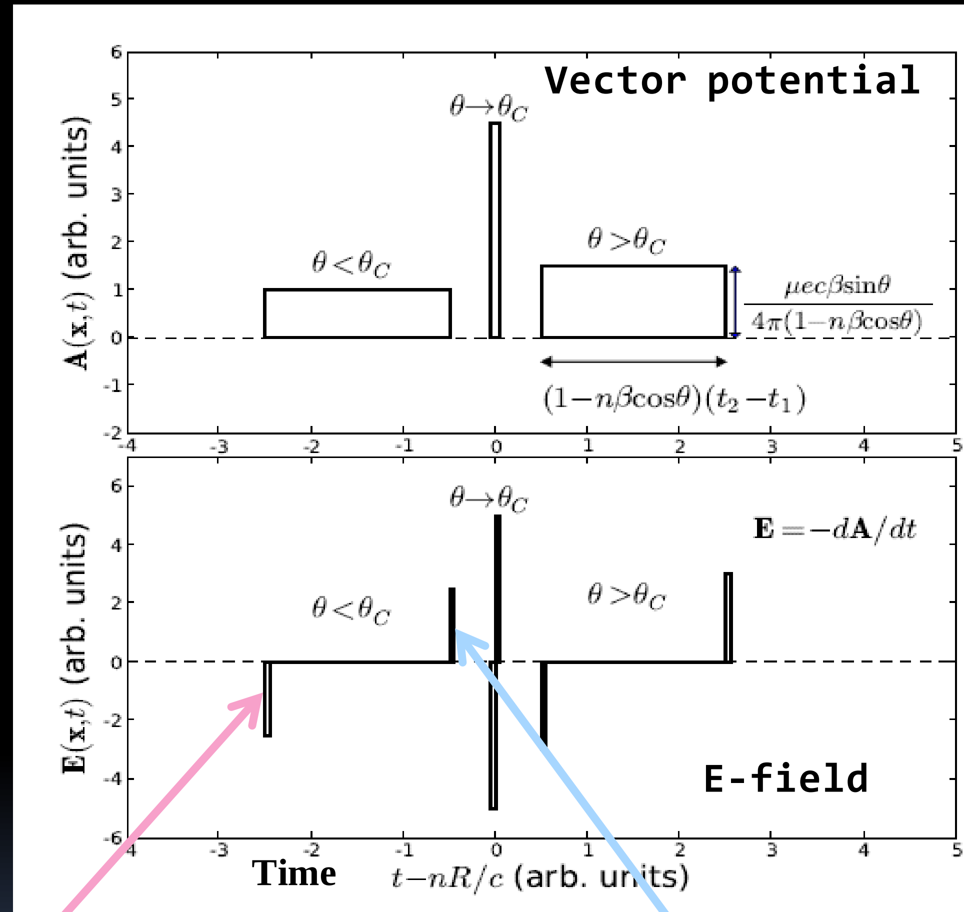
CHERENKOV Radiation

$$RA(t,\theta_C) = \left[\frac{e\mu_r}{4\pi\epsilon_0 c^2}\right]\delta\left(t - \frac{nR}{c}\right)\mathbf{v}_\perp \delta t$$

Field single track: Time domain

[J. Alvarez Muniz, A. Romero-Wolf, E.Z., PRD 81, 123009 (2010)]

NOTE: "Acceleration" with a grain of salt
Limit of large δt gives Cerenkov radiation (by medium)
Terms of adjacent sub-tracks give large cancellations



"Acceleration" "Decceleration"

$$R\mathbf{E}(t,\theta) = -\frac{e\mu_r}{4\pi\epsilon_0 c^2}\mathbf{v}_\perp \frac{\delta\left(t - \frac{nR}{c} - (1 - n\beta\cos\theta)t_1\right) - \delta\left(t - \frac{nR}{c} - (1 - n\beta\cos\theta)t_2\right)}{(1 - n\beta\cos\theta)}.$$

Fourier transform => ZHS

[E.Z., F. Halzen, T. Stanev PRD45 (1992) 386]

(Fraunhofer limit)

$$\vec{E}(\omega) = i\omega \frac{1}{R} e^{i(overall-phase)} v_{\perp} \frac{e^{i(\omega - \vec{k}\cdot\vec{v})\delta t} - 1}{i(\omega - \vec{k}\cdot\vec{v})}$$

$$v_{\perp}\delta t \frac{\sin\left[(1-n\beta\cos\theta)\omega t\right]}{(1-n\beta\cos\theta)\omega t}$$

if ω=0
or θ=θ$_c$
or δt=0

$$v_{\perp}\delta t$$

tracklength

State-of-the-art:
simulations AIRES /CORSIKA +
Zas-Halzen-Stanev algorithm
(classical electromagnetism)

Askary'an effect: excess charge

SOVIET PHYSICS JETP   VOLUME 14, NUMBER 2   FEBRUARY, 1962

EXCESS NEGATIVE CHARGE OF AN ELECTRON-PHOTON SHOWER AND ITS COHERENT RADIO EMISSION

G. A. ASKAR'YAN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor March 24, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) 41, 616-618 (August, 1961)

We investigate the excess of electrons in an electron-photon shower. This excess is caused by annihilation of the positrons in flight and by the Compton and δ-electrons in the cascade. It is shown that at the maximum of the shower the excess may comprise ten percent of the total number of shower particles. The Cerenkov radiation from this excess charge in a dense medium is estimated. It is indicated that this radio emission from showers produced by high-energy accelerator particles or cosmic rays in blocks of dense matter can be recorded and used. The possibility of recording radio waves from penetrating particle showers in the moon's ground, by apparatus dropped on the lunar surface, and in underground layers on the Earth in which radio waves can propagate, is also noted.

Unidimensional current

$J(z,t) = v\, Q(z)\, \delta(z - vt)$

Vector potential

$A(t_{obs}, \theta) \approx v\, Q(\zeta) / R$

$$z' = \zeta(t) = \beta \frac{ct - nR}{1 - n\beta\cos\theta}$$

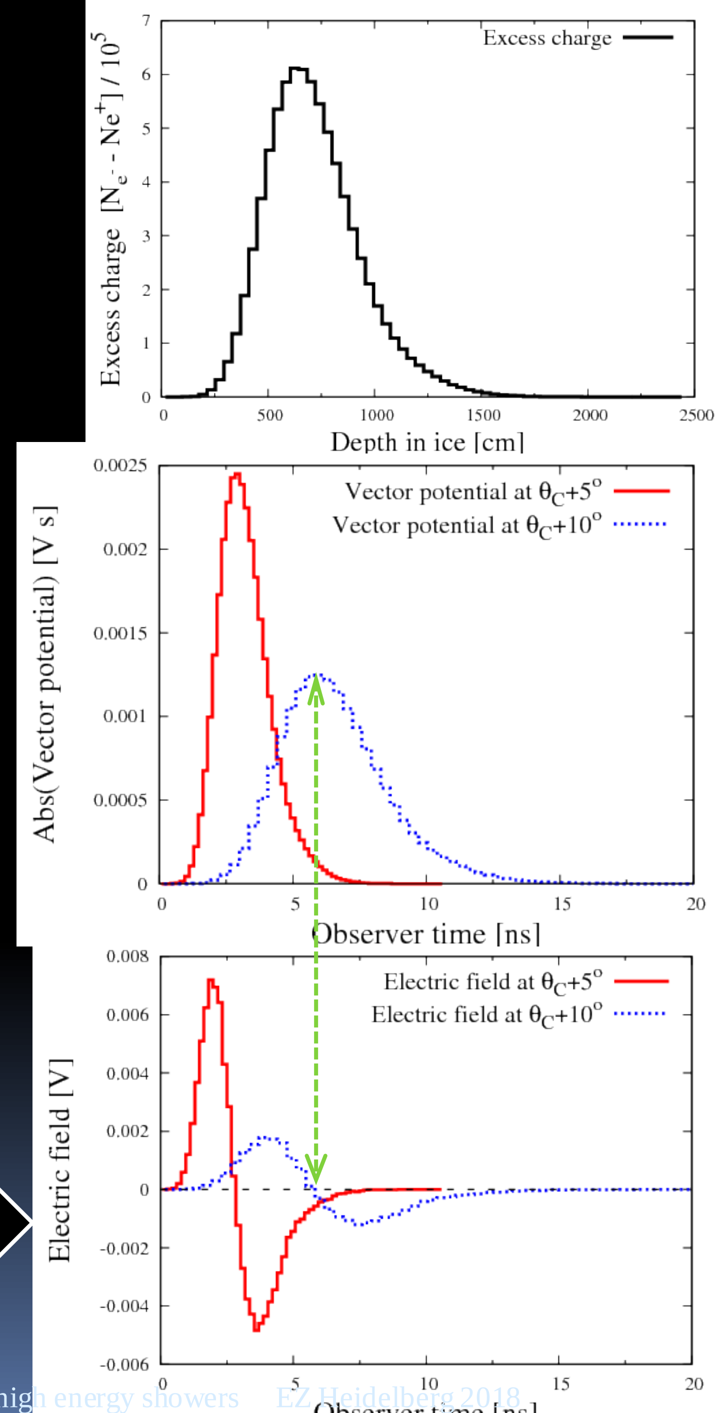
ζ → Retardation + time-compression:
From **z** to **time** t_{obs} (θ – dependent)

$t_{obs} = z(1 - n\cos\theta)/c + t_0 \qquad t_{obs} = t_0$ @ θ_c

Electric field

$E(t_{obs}, \theta) = dA(t_{obs}, \theta)/dt_{obs}$

J. A-M, A. RW, E. Z, PRD **81**, 123009 (2010)

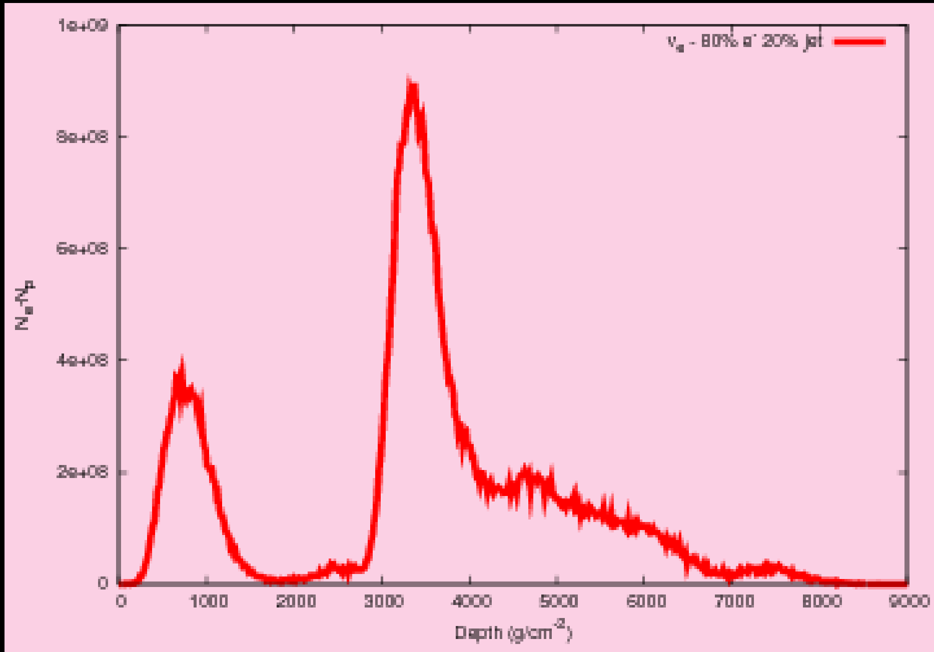


Interesting for neutrino detection

e showers & hadronic debris separate (LPM)

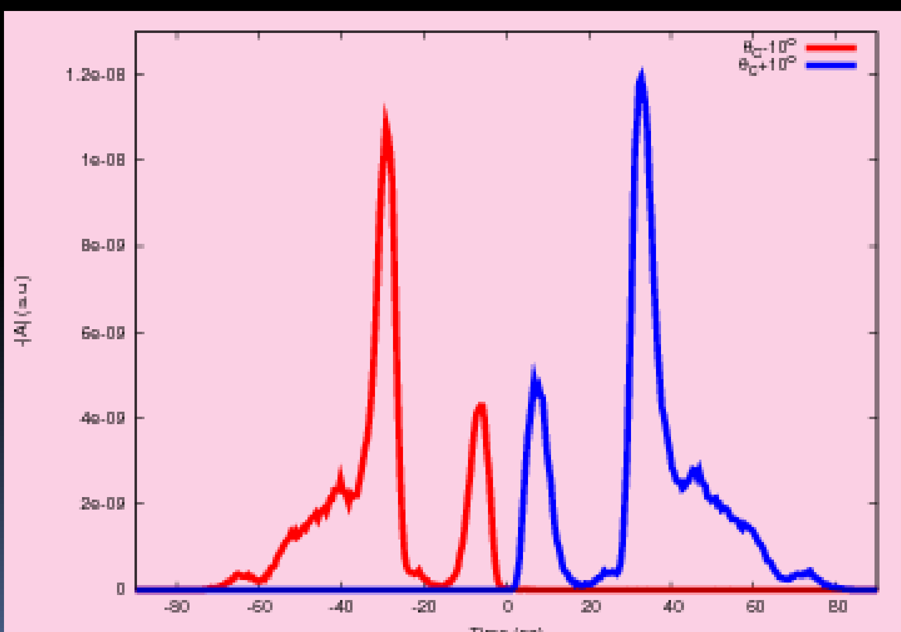
Flavor tagging : ν_e

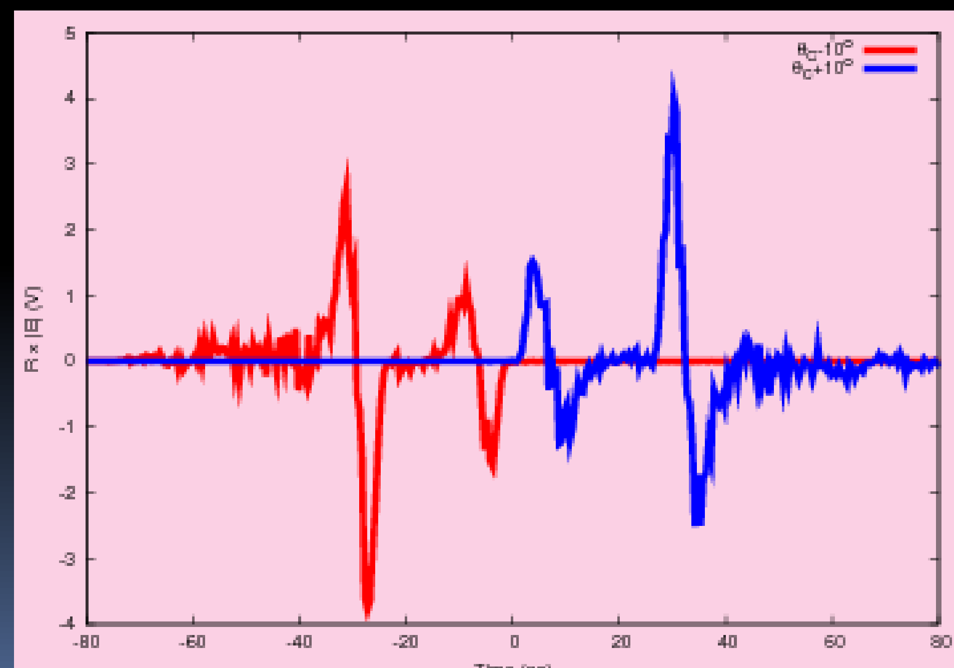
Measure y (energy transfer to hadrons)



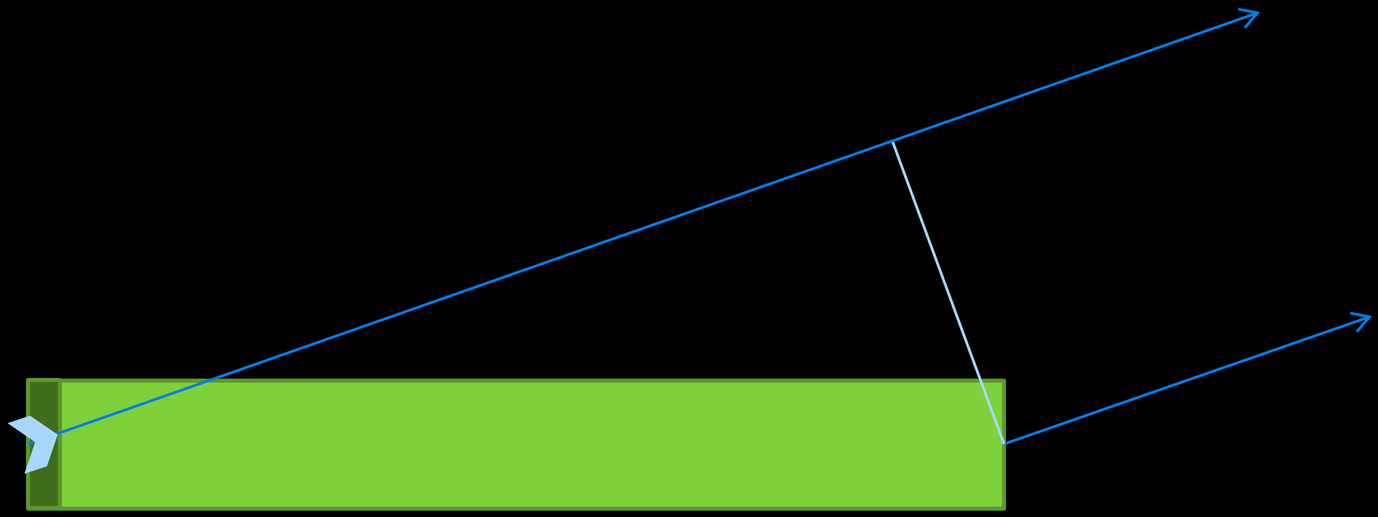
ν_e + N → e + jet

E(ν_e) = 10 EeV
E(hadron jet) = 2 EeV
E(electron) = 8 EeV

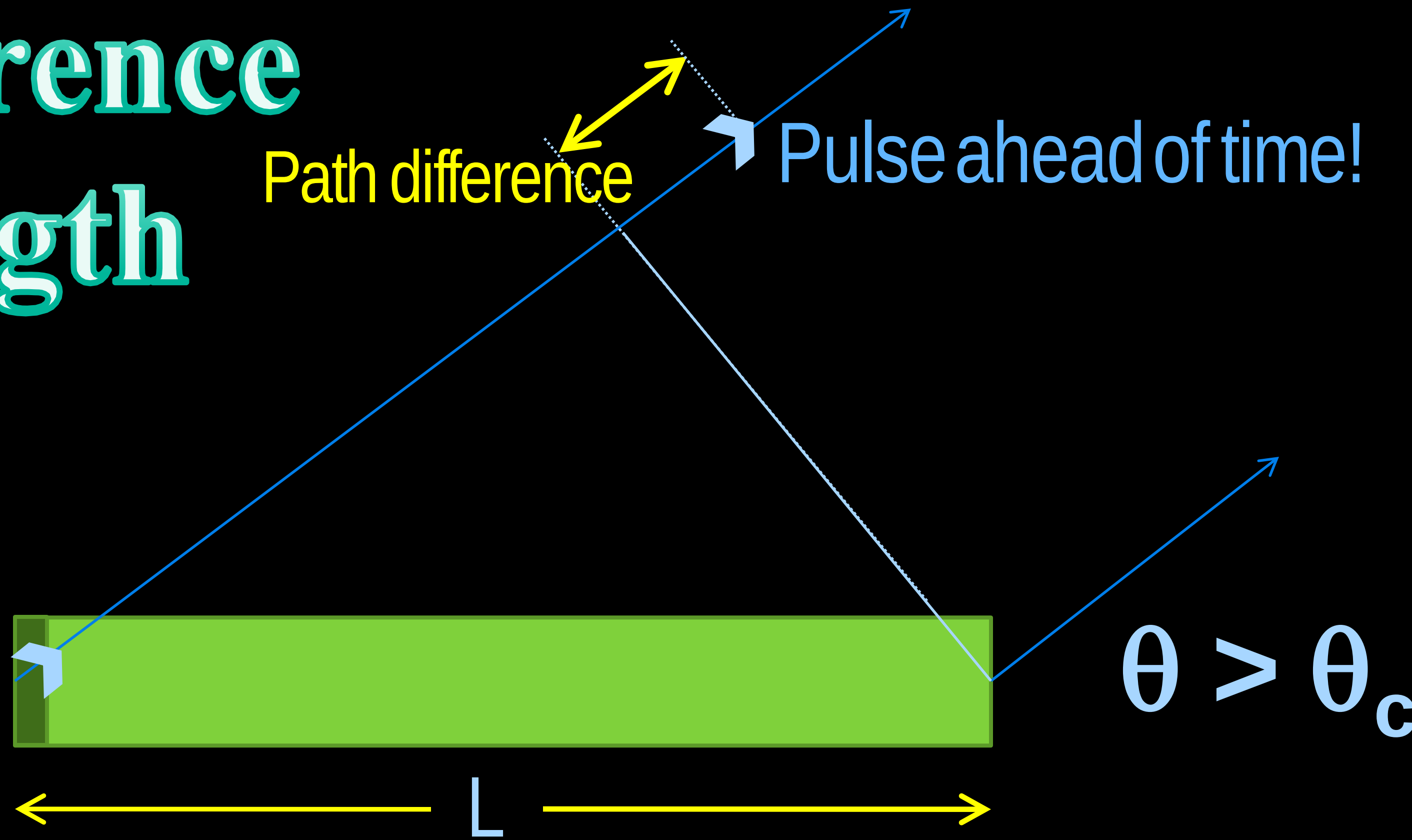




θ_c Cherenkov Angle



Interference 1: length



Emission out of phase

path difference = λ => diffraction minimum

like in a single slit L ~ slit width

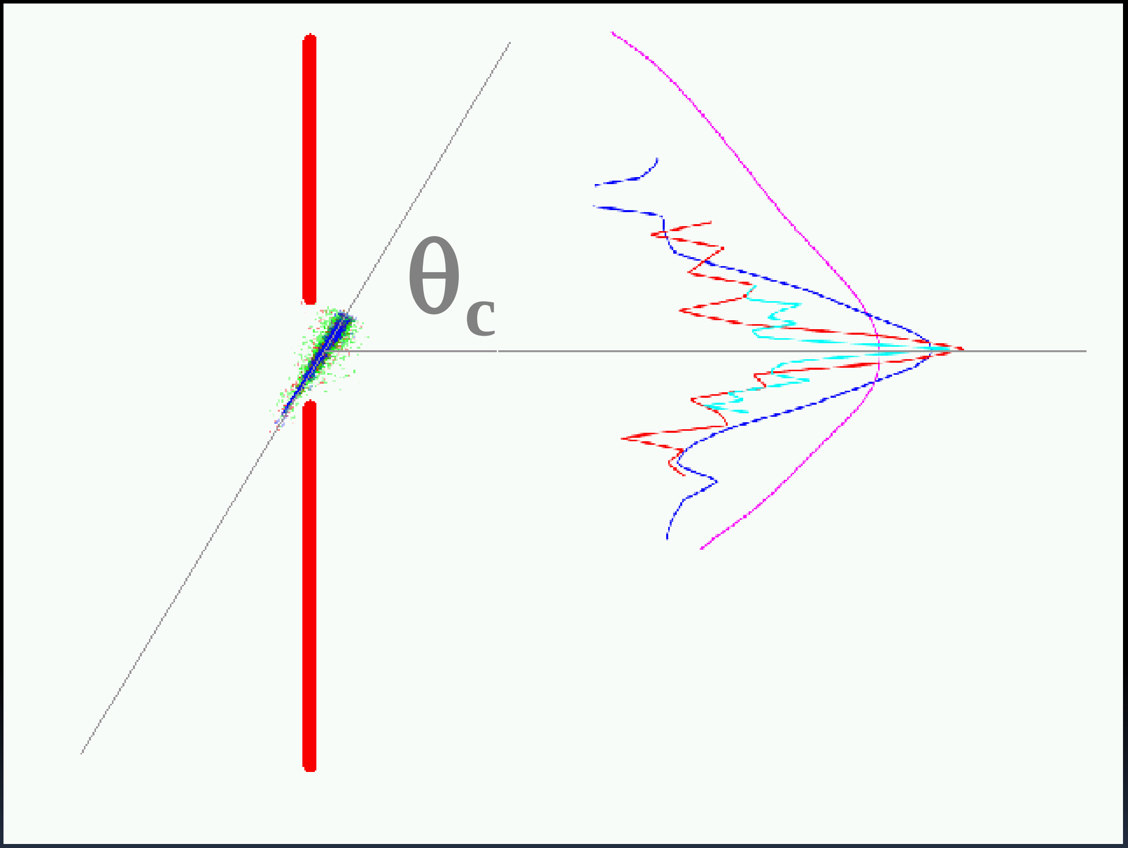
The slit diffraction analogy

If current is "thin":

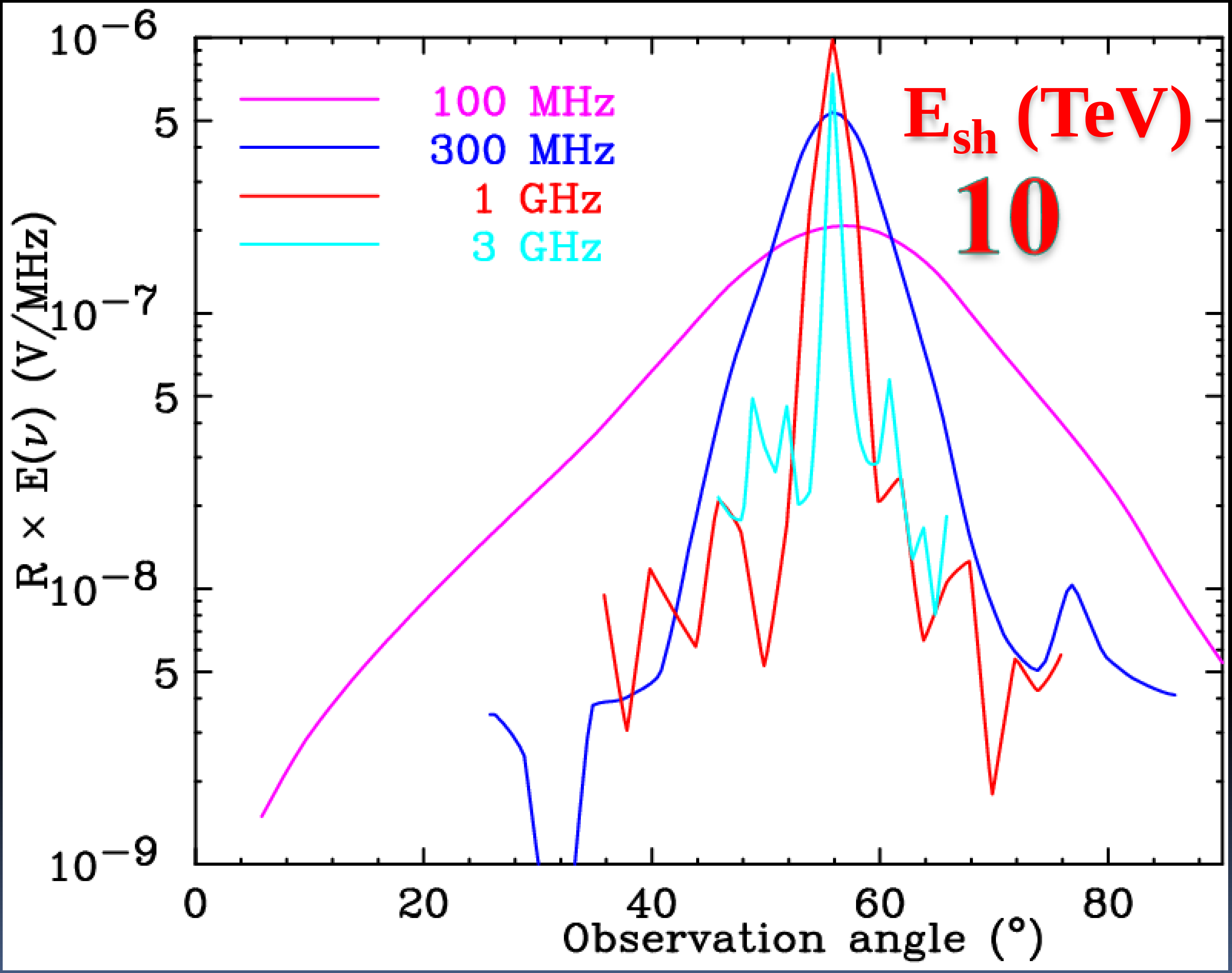
$$\vec{E}(\omega) \propto \frac{i\omega}{R}\int dz Q(z) e^{ikz}$$

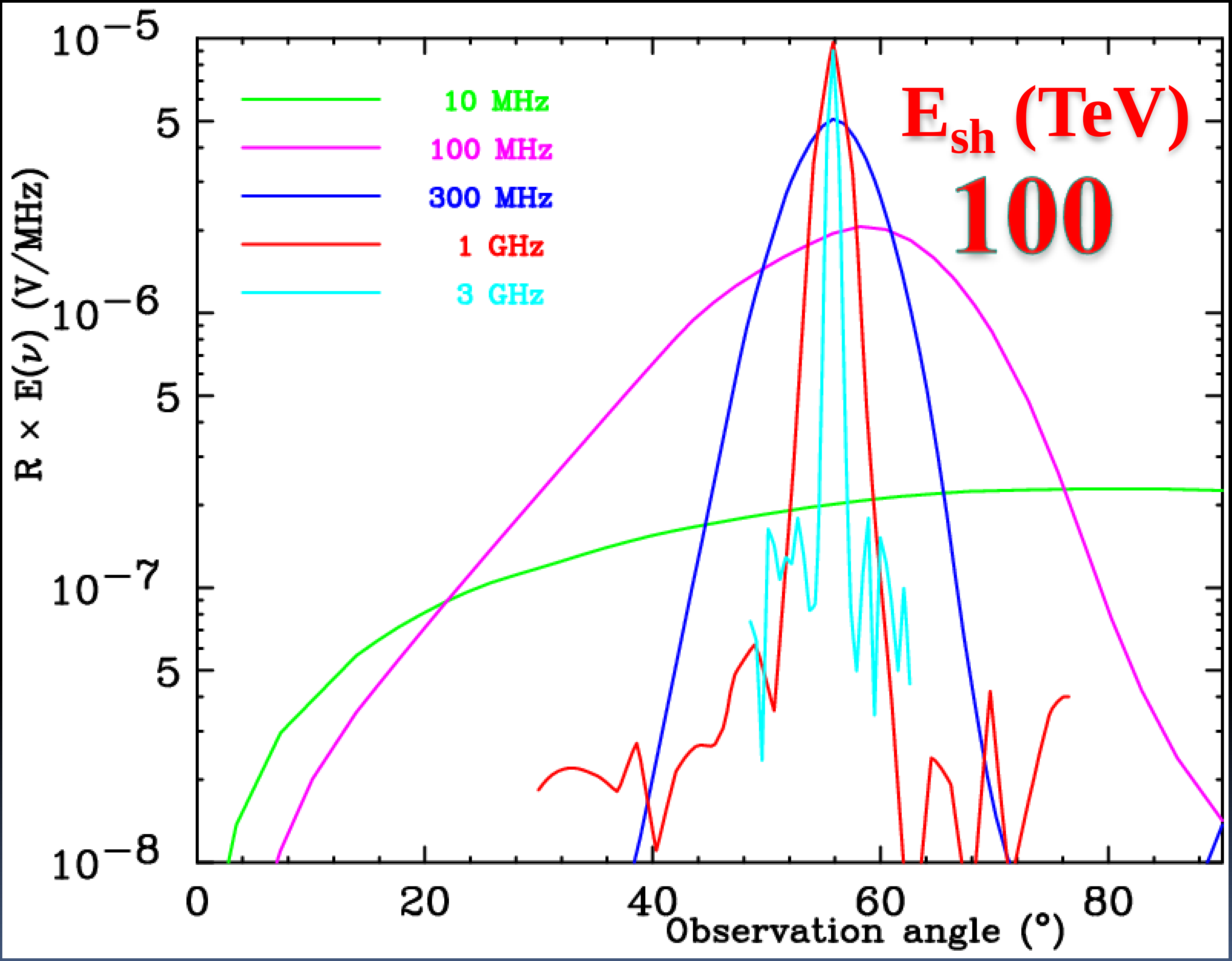
FT with

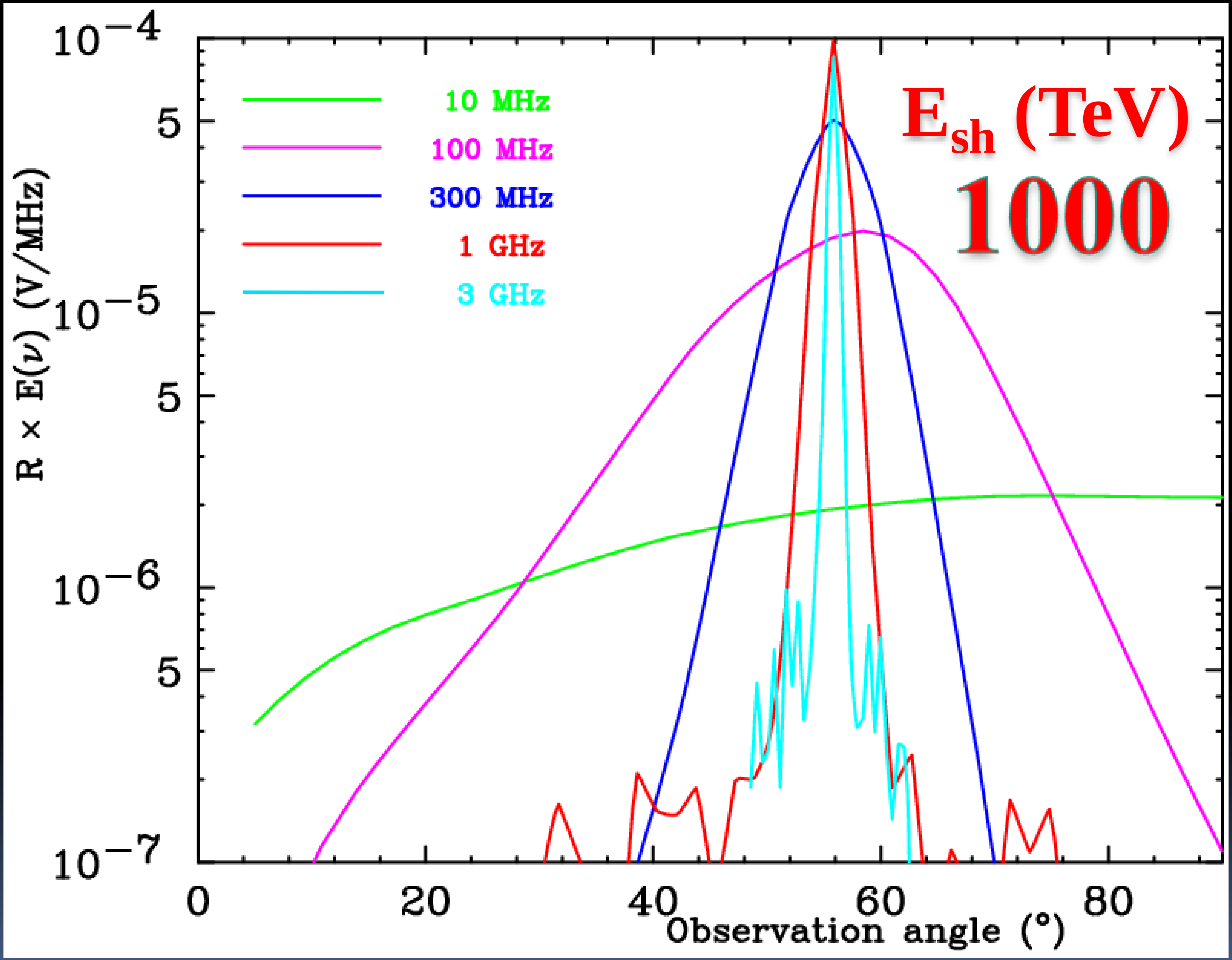
$$k = (1 - n\cos\theta)\frac{\omega}{c}$$



Great scaling properties: reduced fluctuations integrated emission ("calorimetric")

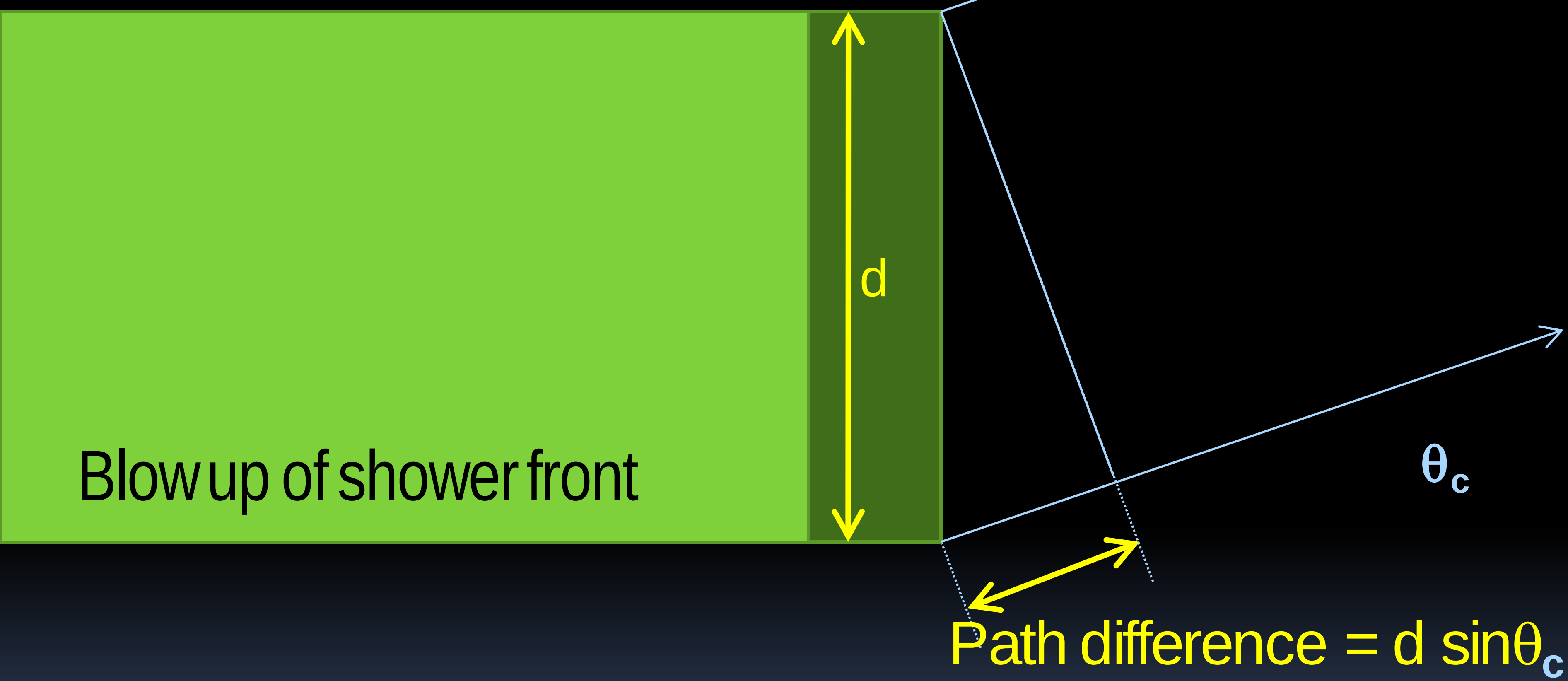

10−6
5
10−7
5
10−8
5
10−9
R × E(ν) (V/MHz)
0
20
40
60
80
Observation angle (°)
100 MHz
300 MHz
1 GHz
3 GHz
E_sh (TeV)
10


10^{-5}
5
10^{-6}
5
10^{-7}
5
10^{-8}
$R \times E(\nu)$ (V/MHz)
10 MHz
100 MHz
300 MHz
1 GHz
3 GHz
E_{sh} (TeV)
100
0
20
40
60
80
Observation angle (°)



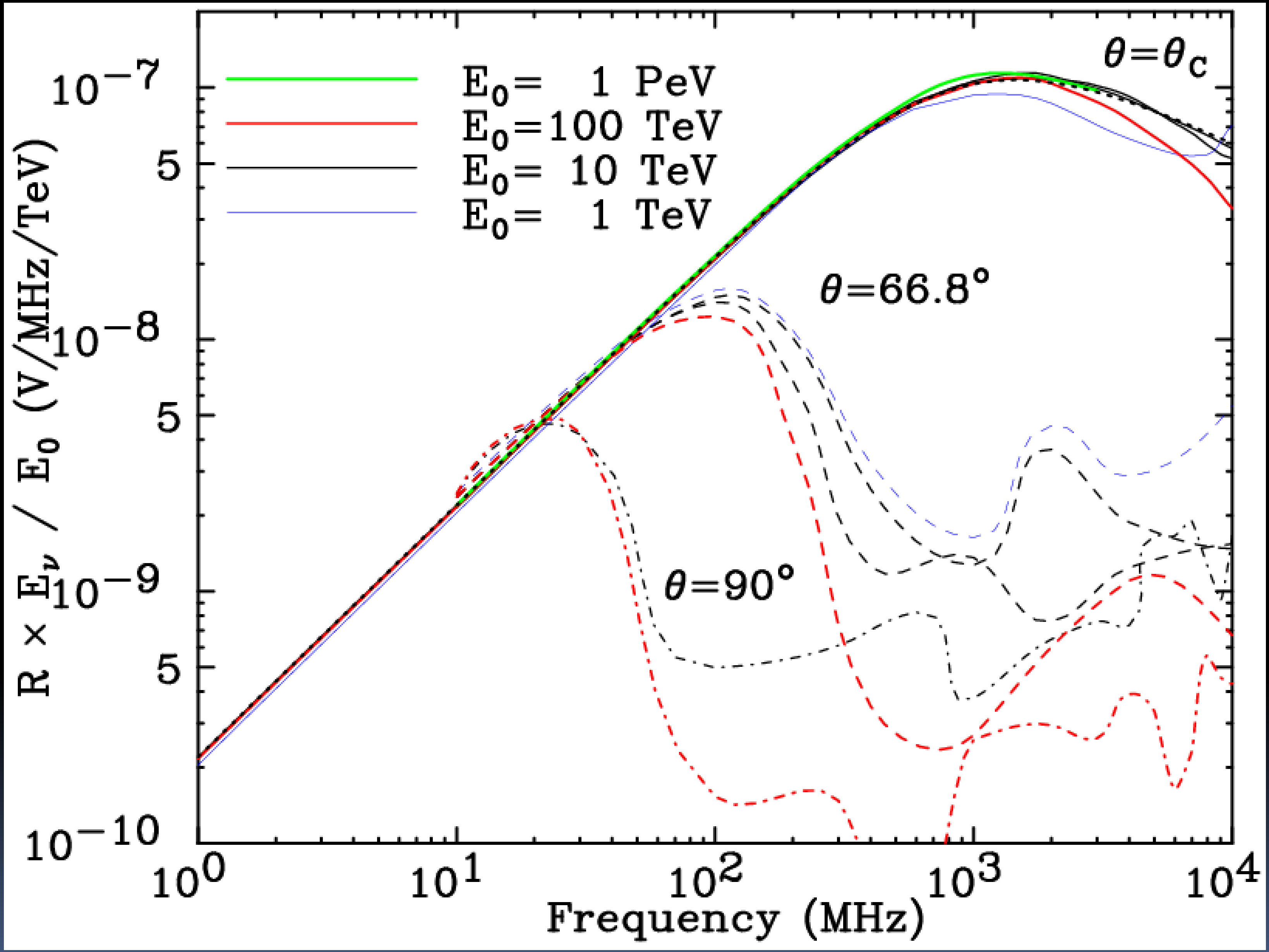
10 MHz
100 MHz
300 MHz
1 GHz
3 GHz
E_{sh} (TeV)
1000
R × E(ν) (V/MHz)
Observation angle (°)

What happens at θ_c? 2: ldf



In Cherenkov direction: $d \sin\theta = \lambda$

Interference minimum at lower λ (higher frequency)



E0= 1 PeV
E0=100 TeV
E0= 10 TeV
E0= 1 TeV
θ=θc
θ=66.8°
θ=90°
R × Eν / E0 (V/MHz/TeV)
Frequency (MHz)
10−7
5
10−8
5
10−9
5
10−10
10^0
10^1
10^2
10^3
10^4

Why is the atmosphere so different?

The Cherenkov angle is small ~ 1^0

$$\mathbf{A} = \frac{\mu}{4\pi}\int \frac{\mathbf{J}_\perp(\mathbf{x}',t')}{|\mathbf{x}-\mathbf{x}'|}\delta\left(\sqrt{\mu\epsilon}|\mathbf{x}-\mathbf{x}'| - (t-t')\right) d^3\mathbf{x}' dt'$$

$J_\perp = Q\ v_\perp \sim 0.2 N_e c$ **sin θ** $\sim 0.003\ N_e c$ (Askary'an)

B $\longrightarrow$ transverse current $\sim v_\perp^{drift} \sim qB_\perp/\rho \sim 0.04c$

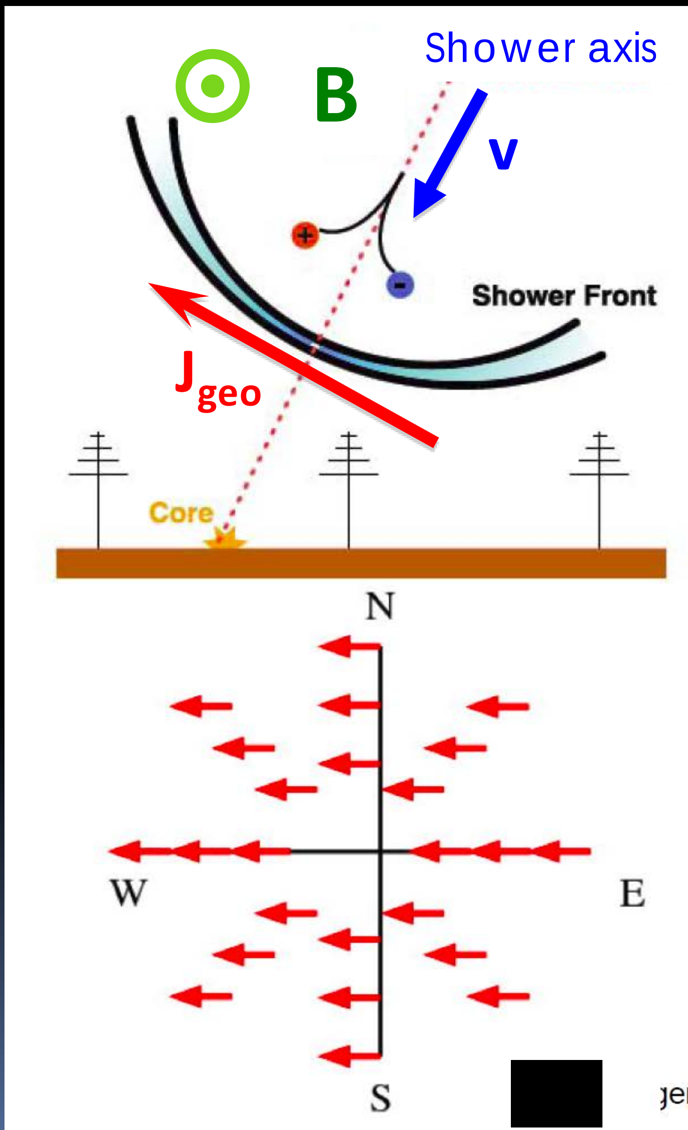
O. Scholten et al. ApP29(2008)94

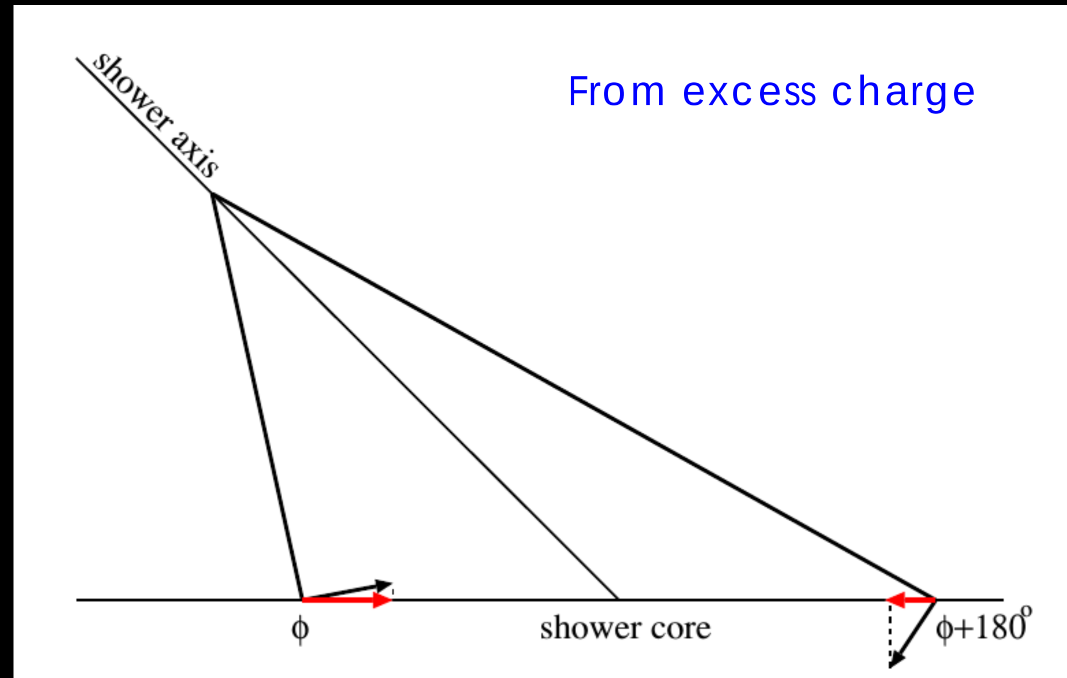
$J_\perp = Q\ v_\perp^{drift} \sim 0.04\ N_e c$ (geomagnetic) often **dominant**

Depends on $\sin(\alpha)$ [angle between shower axis and B field]

Polarization of two components is different

Geomagnetic





However new complex issues:
Loss of symmetry (mixed patterns)
There is a varying refractive index
There is curvature of the atmosphere
…

Lessons from experiments

Many activities pursued

>89 On Moon from Earth: GLUE, ATCA, LUNASKA, LOFAR …

R.D. Dagkesamanskii, I.M. Zheleznykh, Sov. Phys. JETP Lett. 50(1989)259 …

>96 In Ice: Rice, ARA, ARIANNA …

G. Frichter; D.Besson; D. Seckel; …

>00 On "lab": SLAC (Silica Sand, Salt, Ice, Air+B), Utah (ARAcalTA) …

P. Gorham, D. Saltzberg et al. PRL86(2001)2802 …

>03 In air: LOPES, CODALEMA, AERA, LOFAR, Tunka-Rex…

D.Ardouin; H. Falcke …

>03 In ice from air: ANITA …

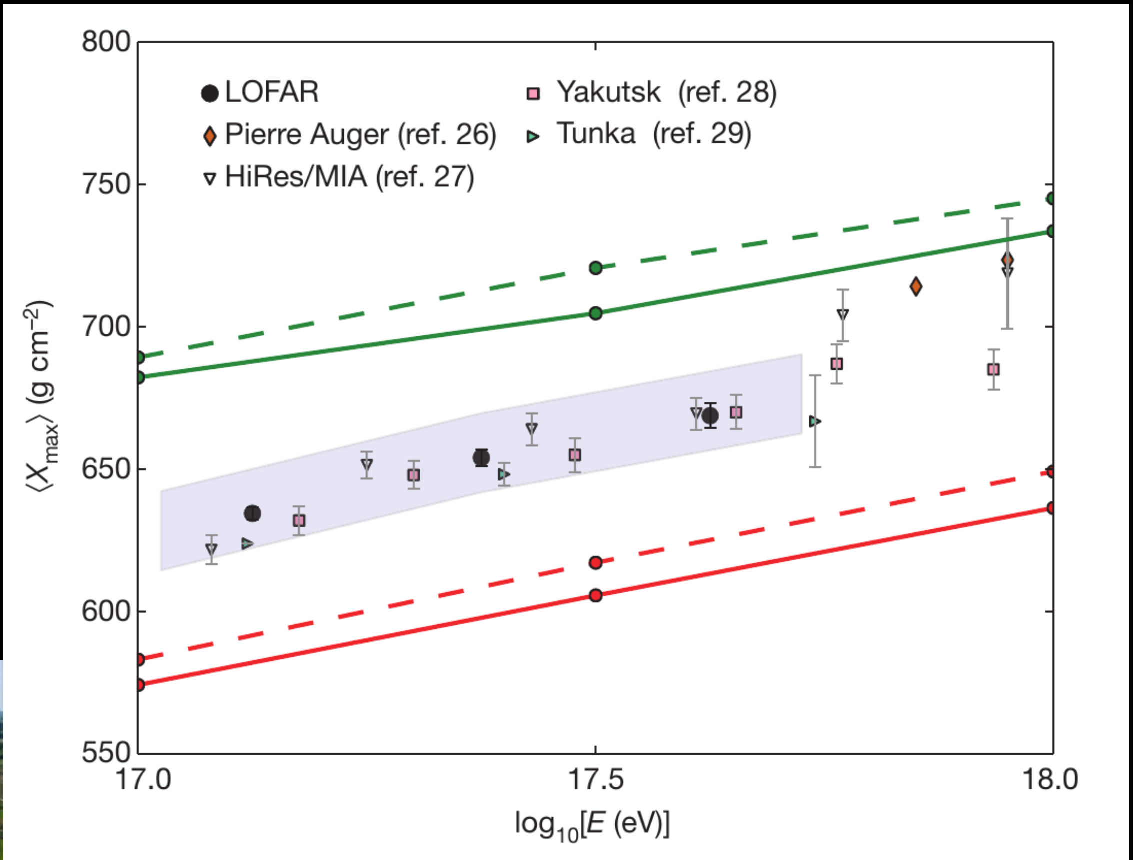
P. Gorham, et al. PRL96(20006)171101

>10 in air microwave: MIDAS, CROME, EASIER, MAYBE ...

P. Privitera; A. Lettessier-Selvon; R. Smida; V. Verzi, …

LOFAR

Buitnik, S. et al. Nature 531 (2016) 70

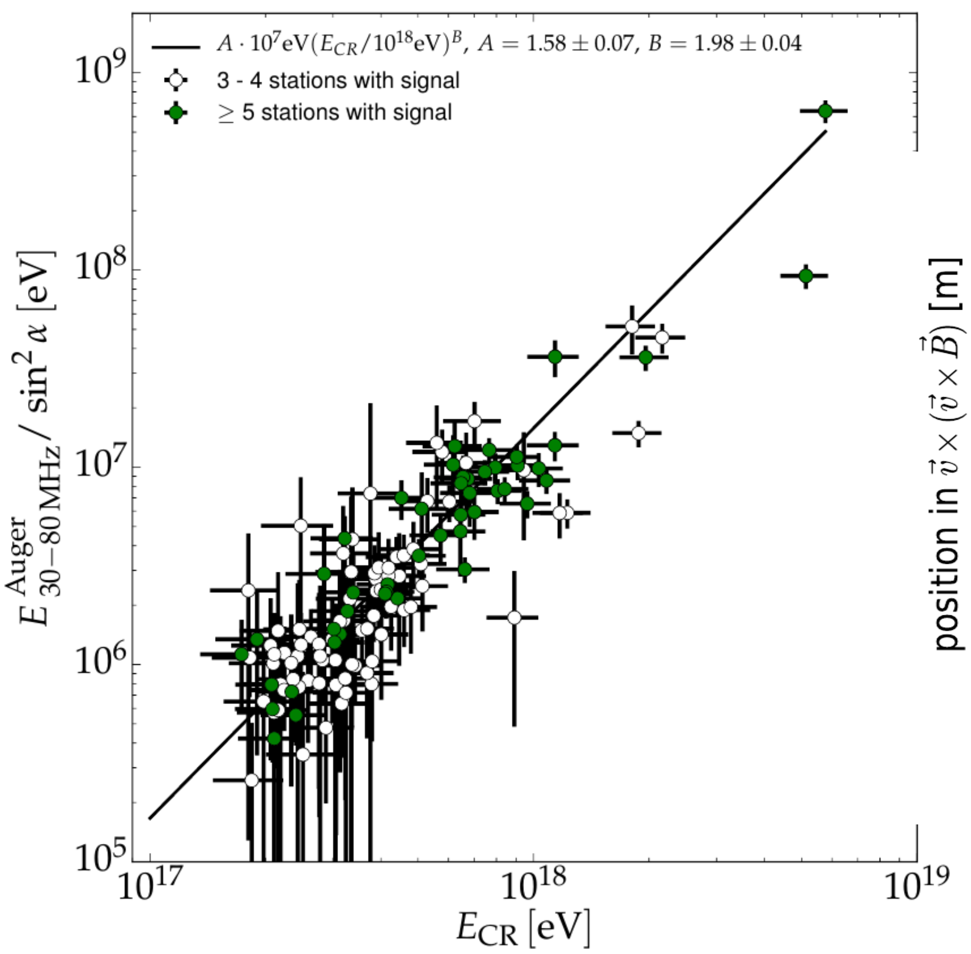


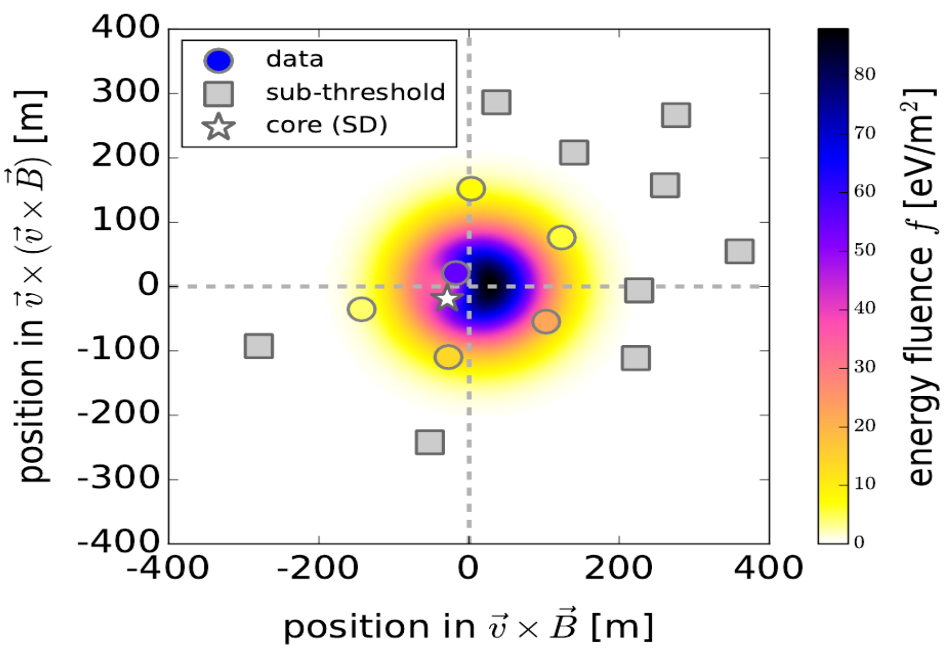
X_{max} reliably measured!

Auger Observatory: AERA

Energy in radio is an excellent energy estimator!

The Pierre Auger Collaboration,
PRL 116, 241101 (2016); PRD 93 122005 (2016)





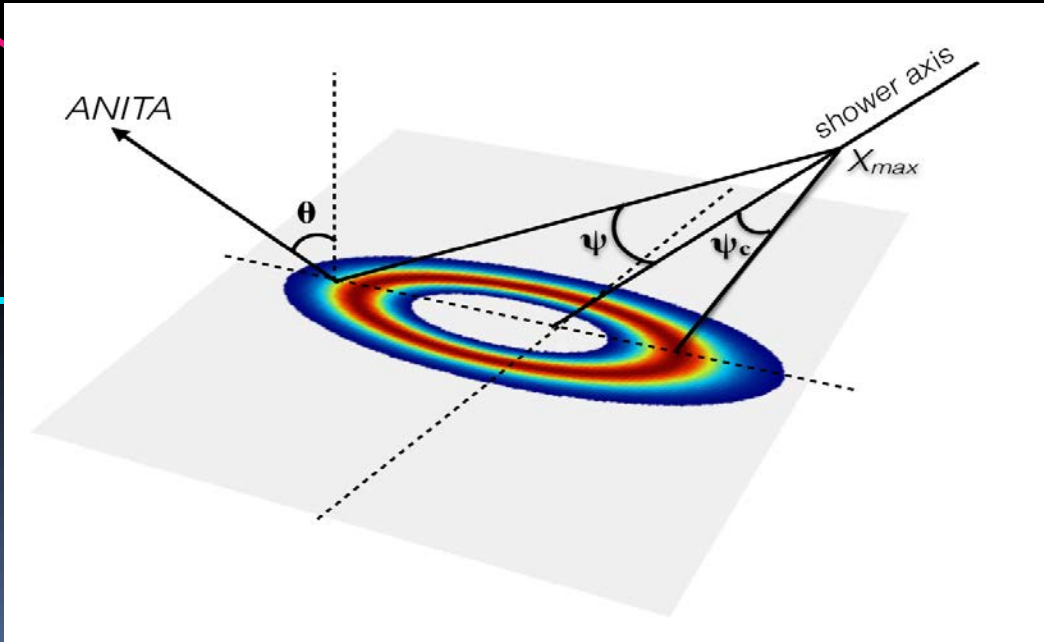
36 km high

ANITA

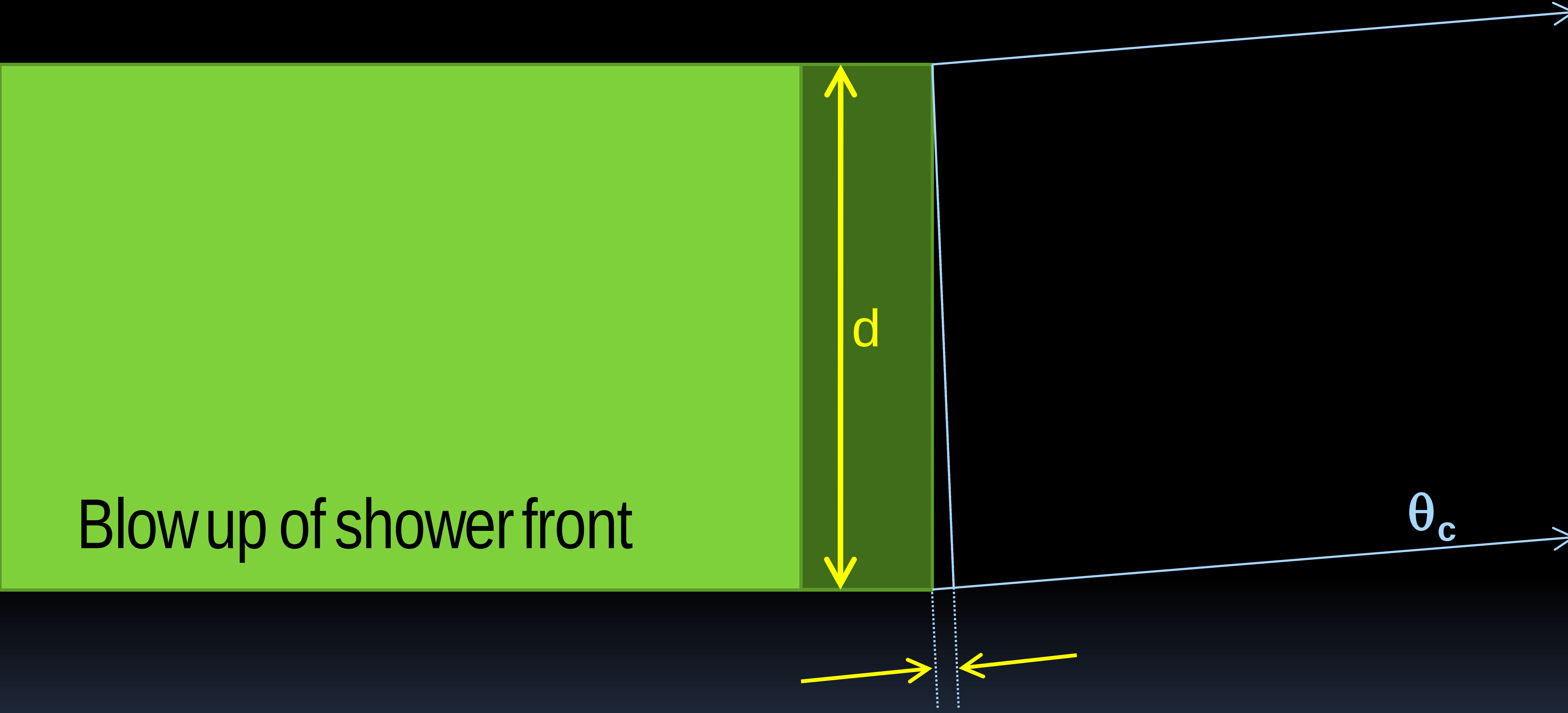
P. Gorham, et al. PRL105(2010)151101

14 events CR detected!
Why GHz radiation?

Ice Surface



Diameter 1000 times larger BUT θ_c VERY small



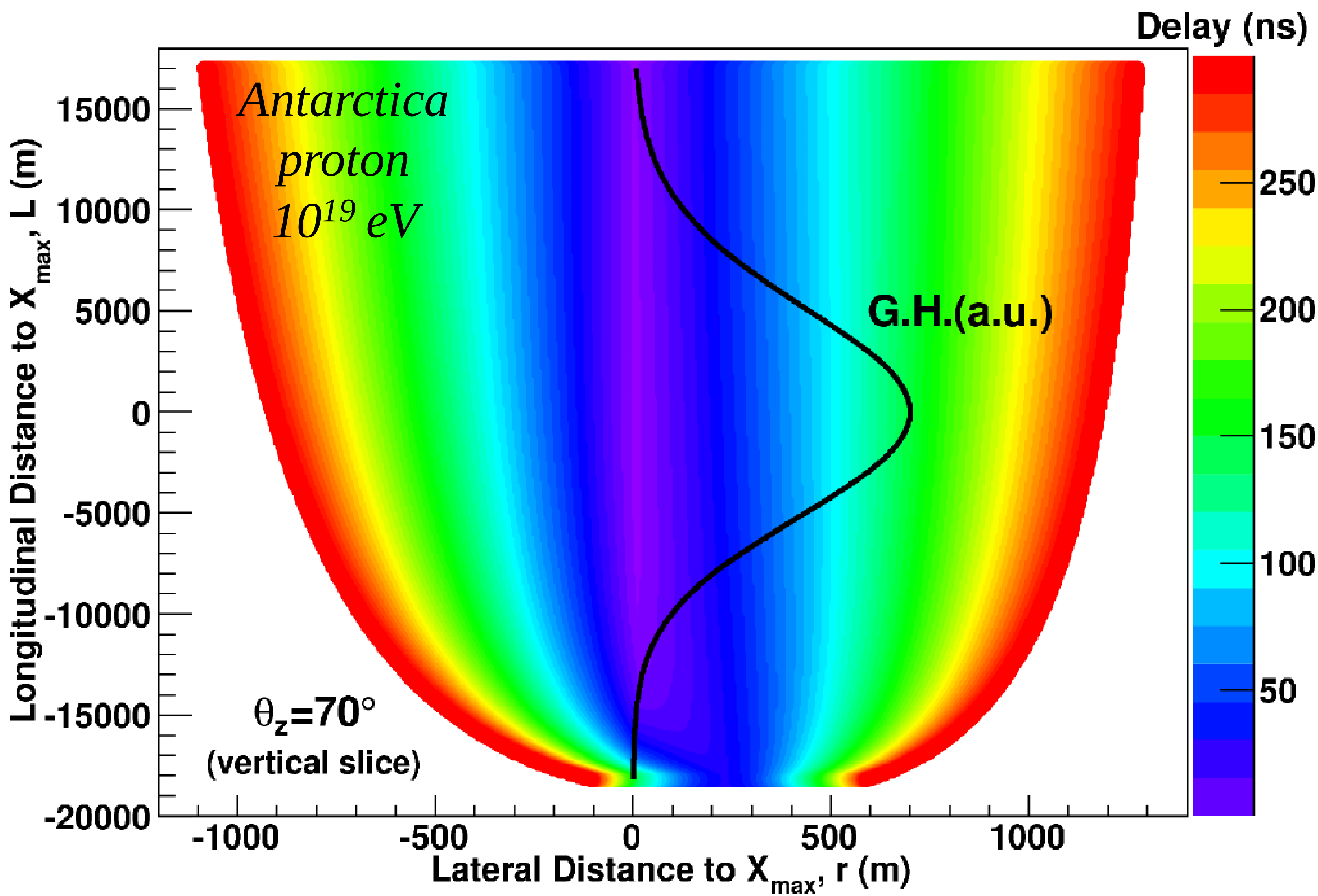
Path difference = d $\sin\theta_c$

At θ_c coherence up to the GHz in spite of scale factor!!

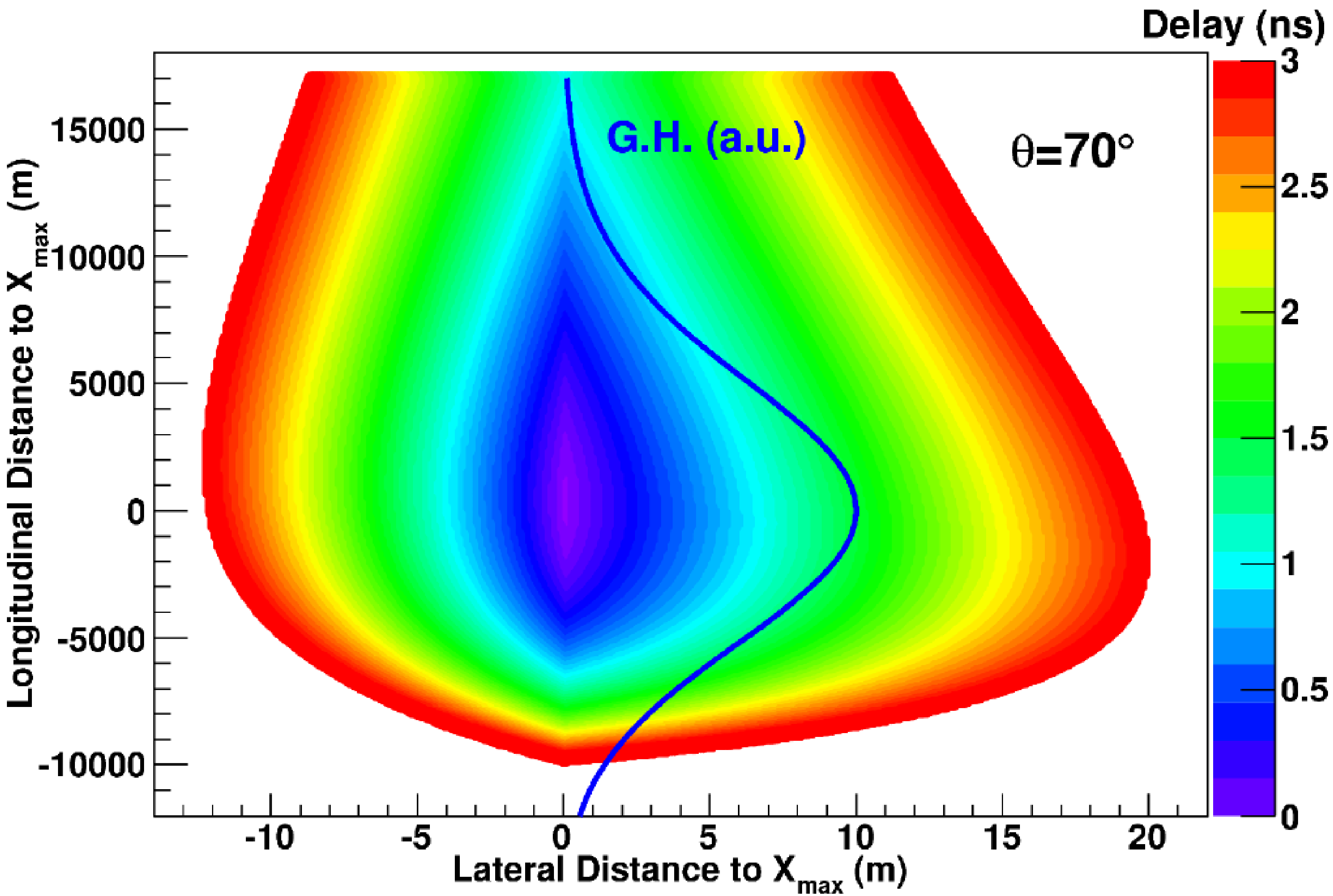
Insight from time delays

Alvarez-Muñiz, et al. PRD 86 (2012) 12300

Observer at position such that shower center (0,0) is viewed viewed at Cherenkov angle

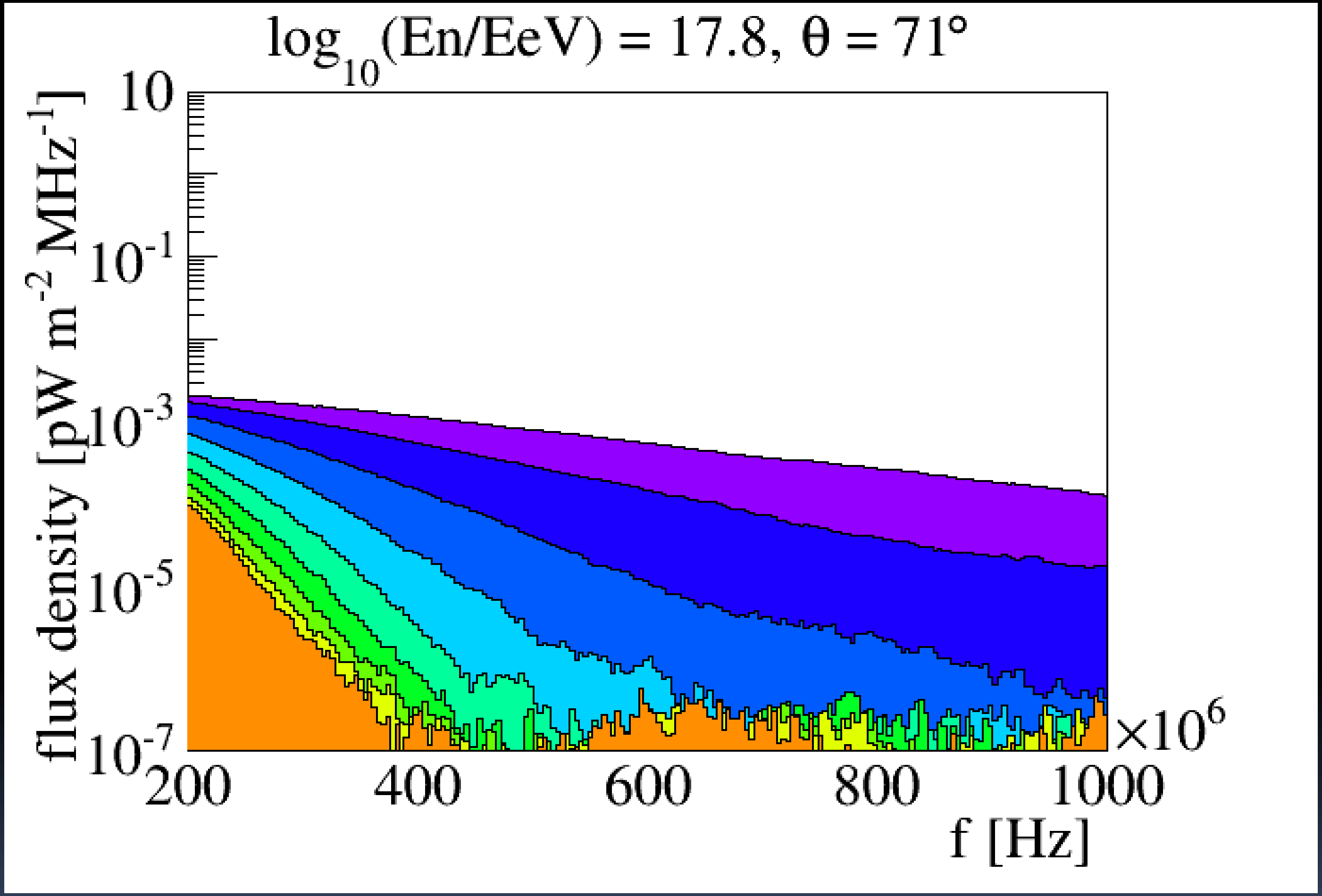


Blow up of central region



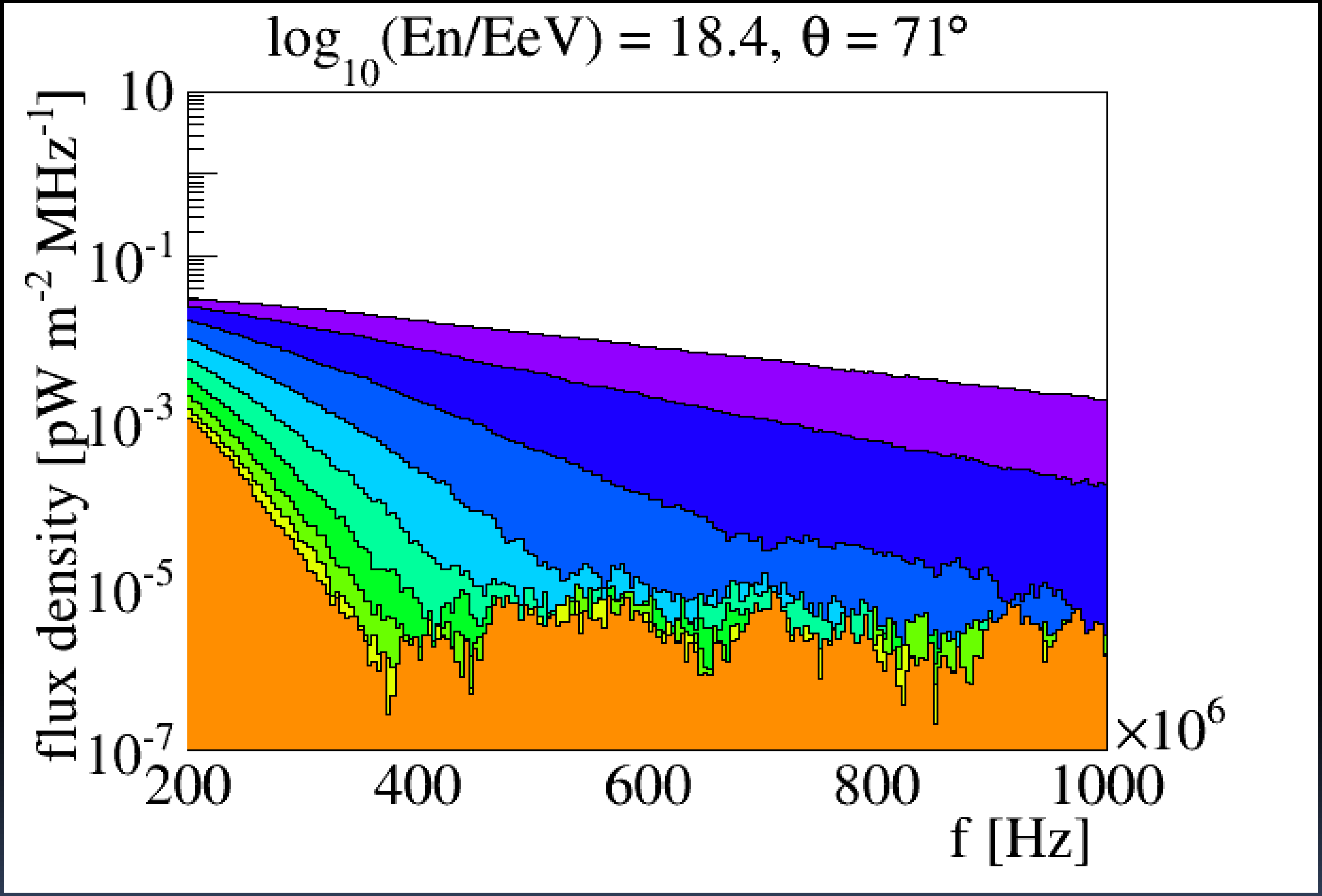
Different spectra as we get away from Cher angle

Inner cone



$\psi = 0.7^0$
$\psi = 0.62^0$
$\psi = 0.55^0$
$\psi = 0.48^0$
$\psi = 0.4^0$
$\psi = 0.33^0$
$\psi = 0.25^0$
$\psi = 0.18^0$
$\psi = 0.11^0$

Inner cone



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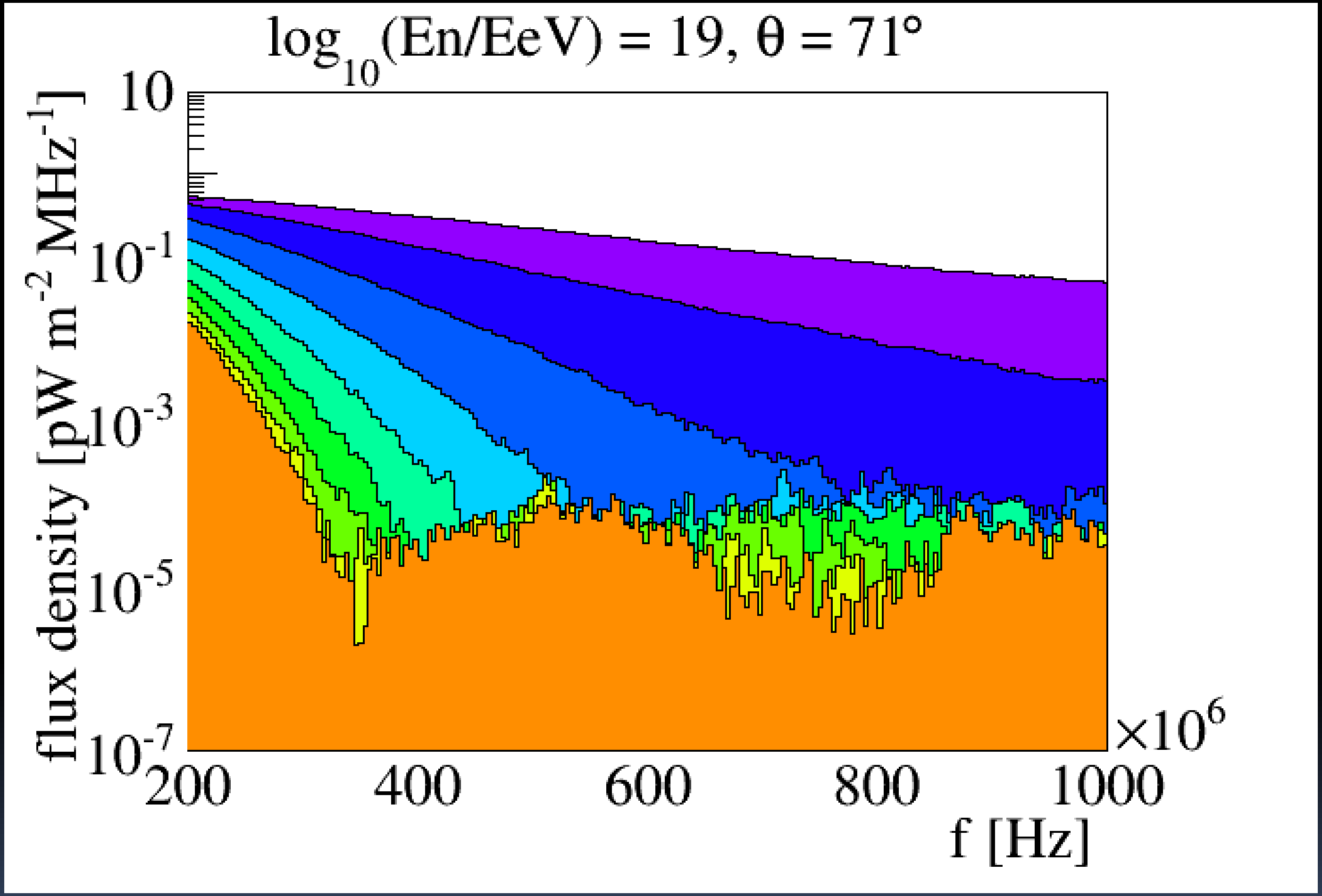
Inner cone



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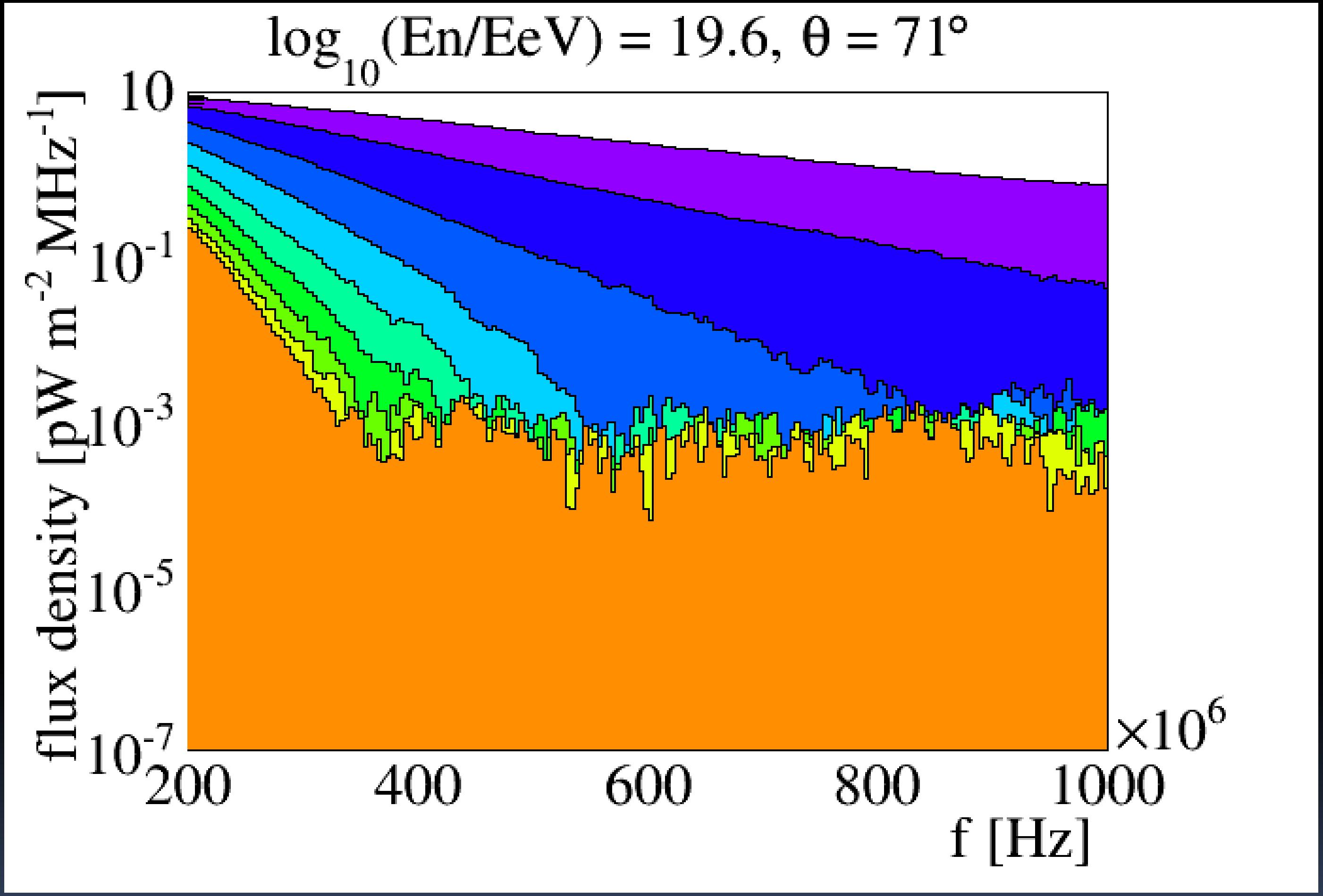
$\psi=0.4^0$
$\psi=0.33^0$
$\psi=0.25^0$
$\psi=0.18^0$
$\psi=0.11^0$

Excellent scaling with energy

Inner cone



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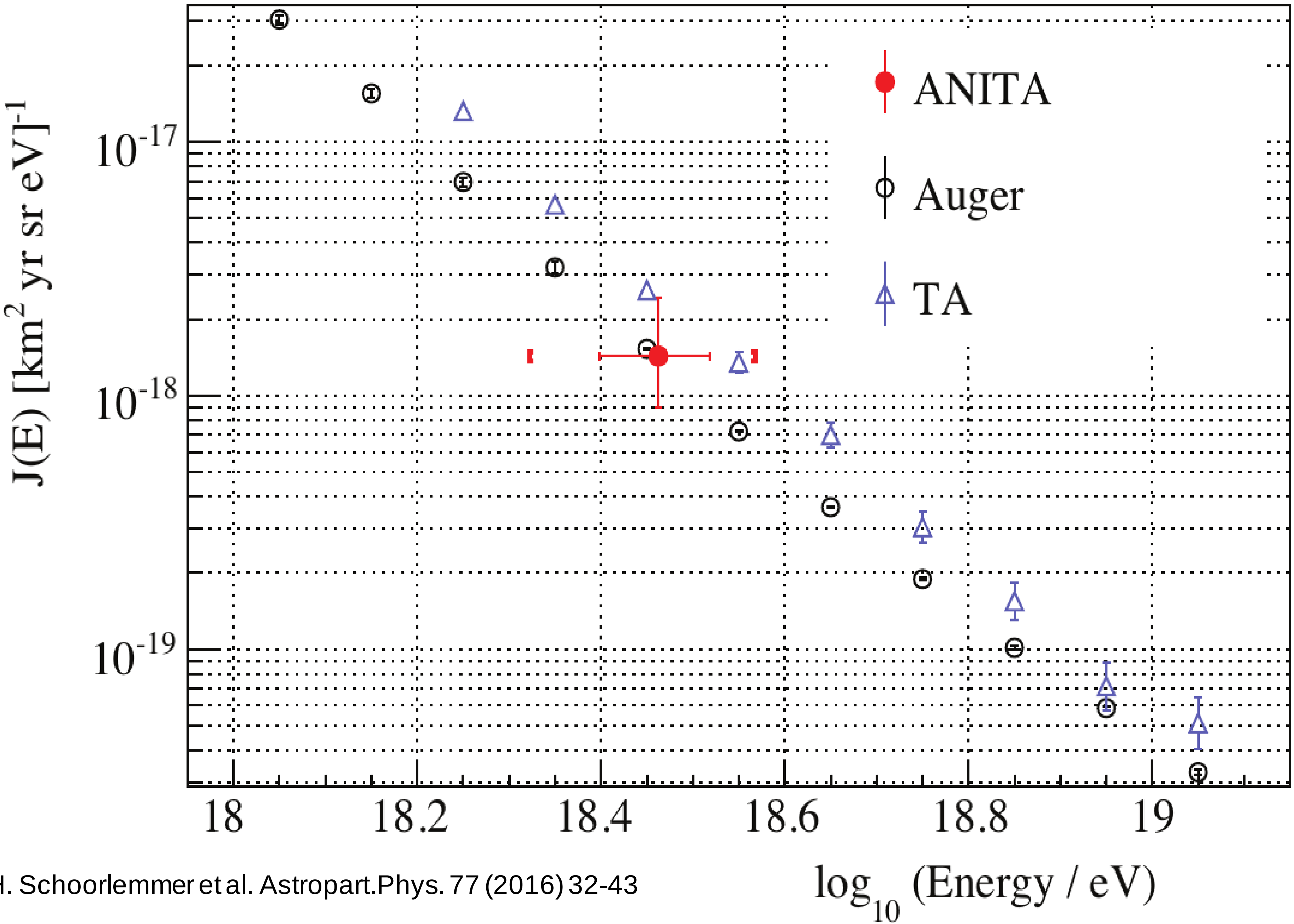
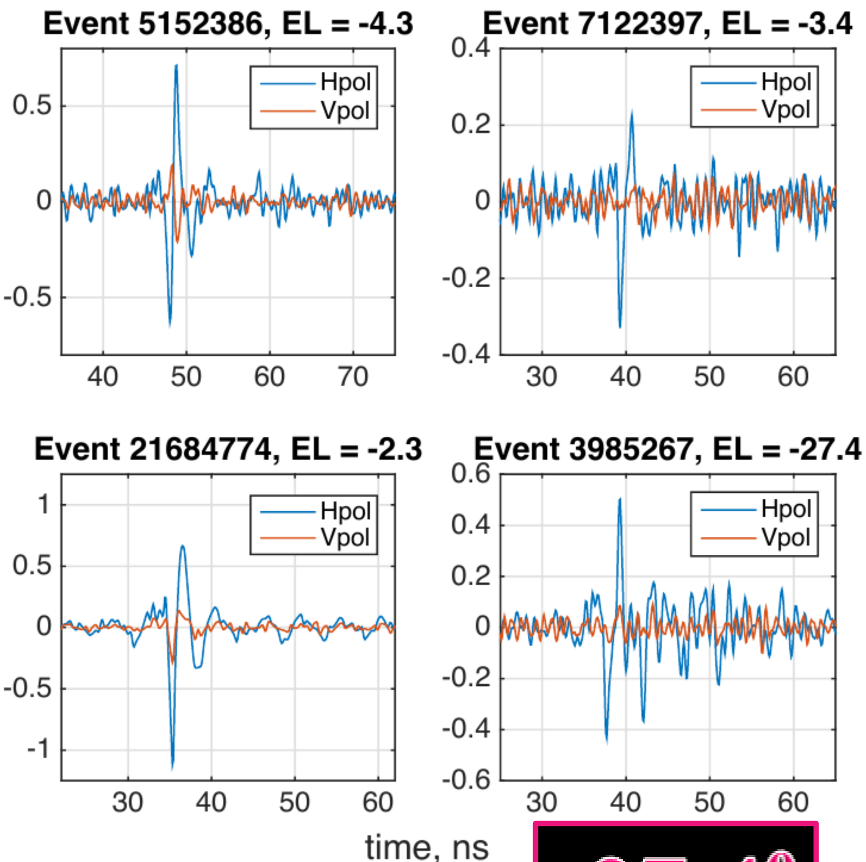


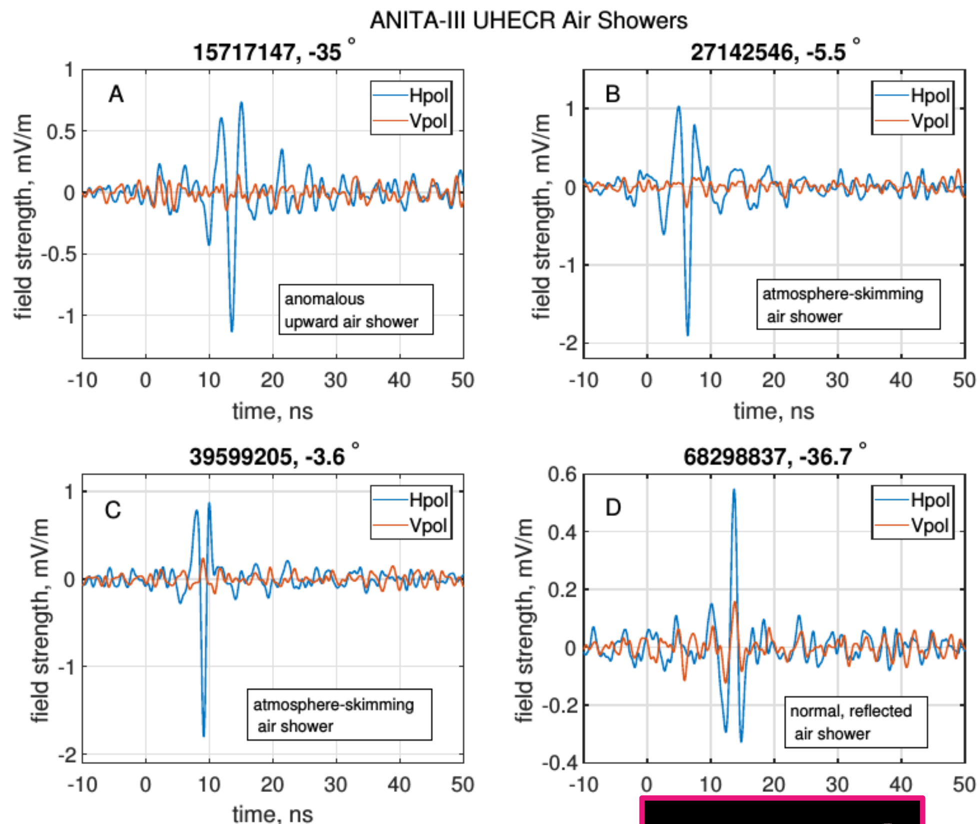
H. Schoorlemmer et al. Astropart.Phys. 77 (2016) 32-43

ANONMALOUS EVENTS

Gorham et al. PRL117(16)071101

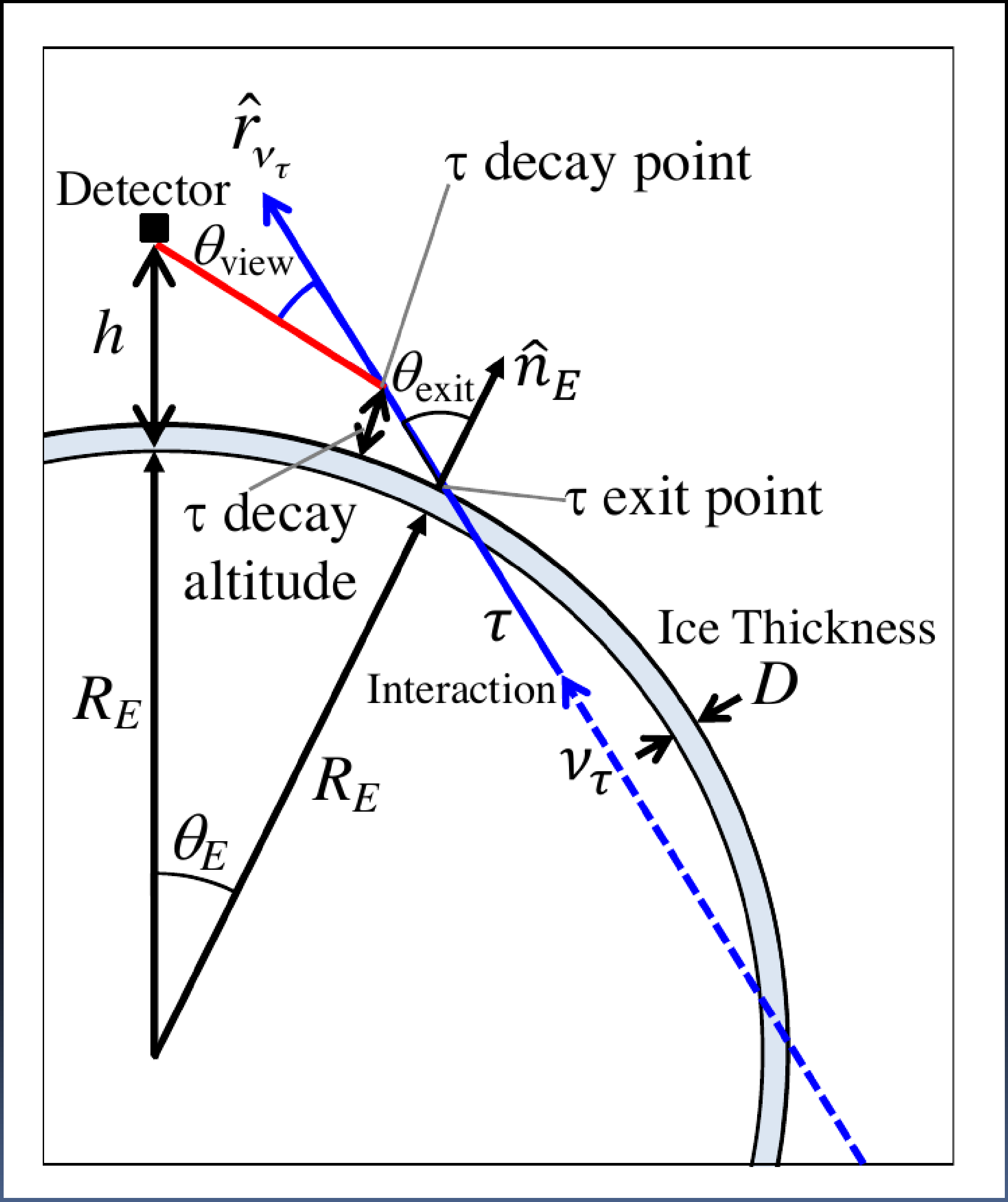
Gorham et al. PRL121(18)161102



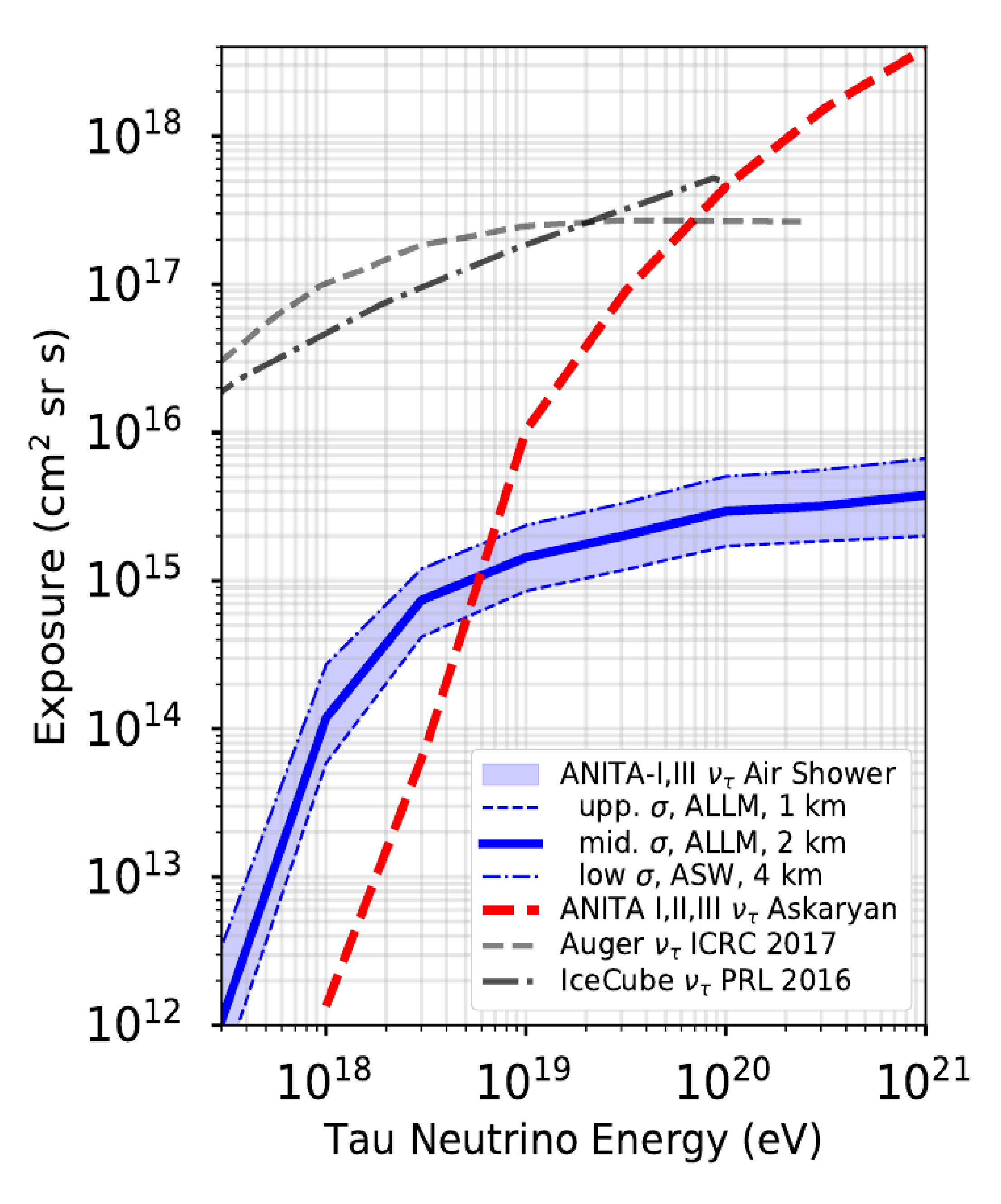


-27.4^0

-36.7^0



$\hat{r}_{\nu_\tau}$
Detector
τ decay point
θ_{view}
h
θ_{exit}
$\hat{n}_E$
τ exit point
τ decay
altitude
τ
Ice Thickness
Interaction
D
R_E
ν_τ
R_E
θ_E



A Romero-Wolf et al.
ArXiv:1811.07261

The future is Big and Bright

URGENT need to explore the PeV to EeV neutrino region

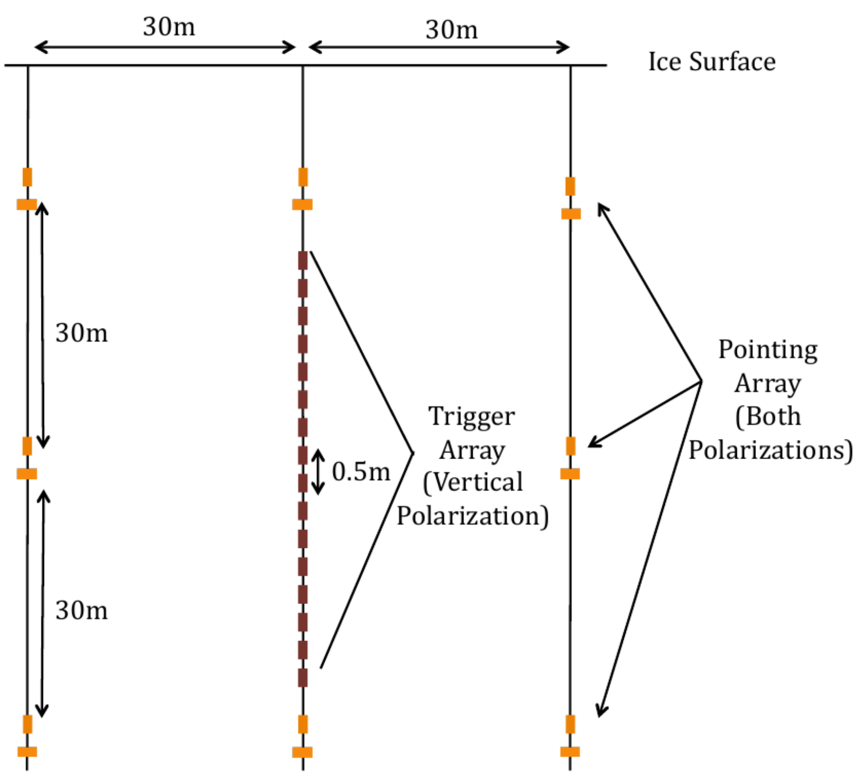
In Ice experiments -> Phased Array, NGR
(Next Generation Radio Array)

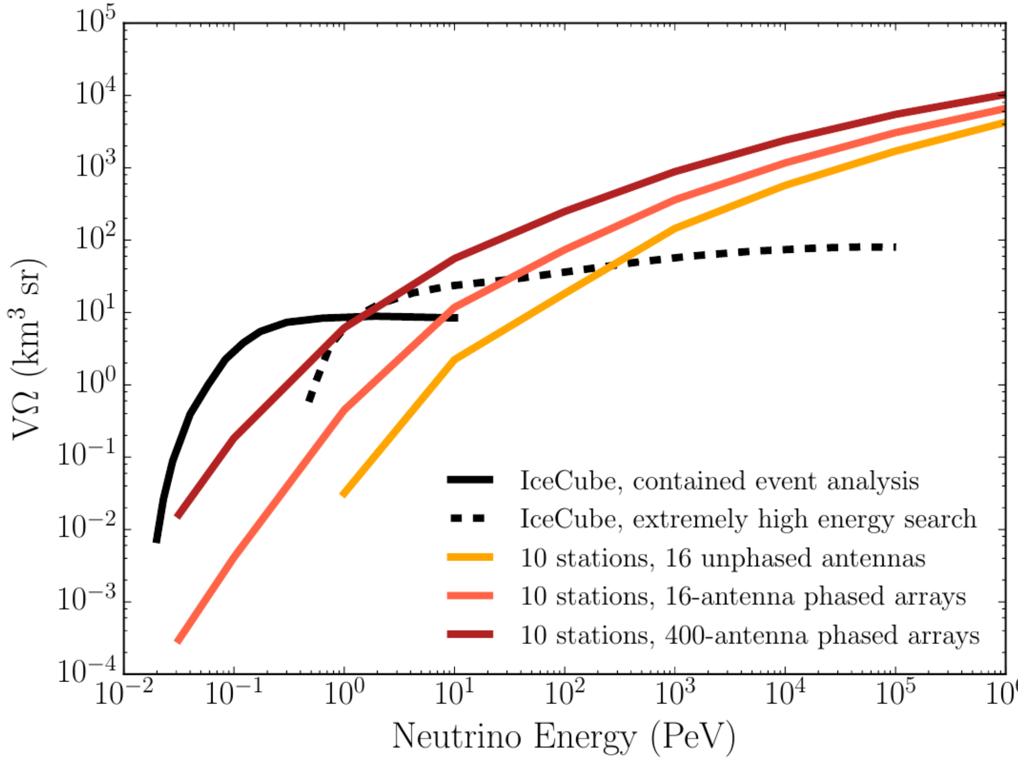
In Air from Ice experiments -> EVA, GRAND

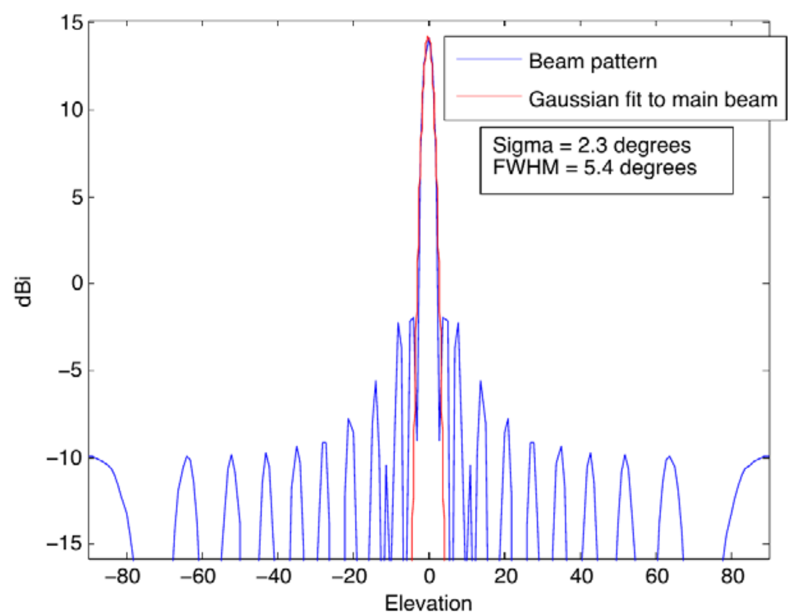
In Air: Auger, SKA, GRAND (neurinos & CR)

Phased array

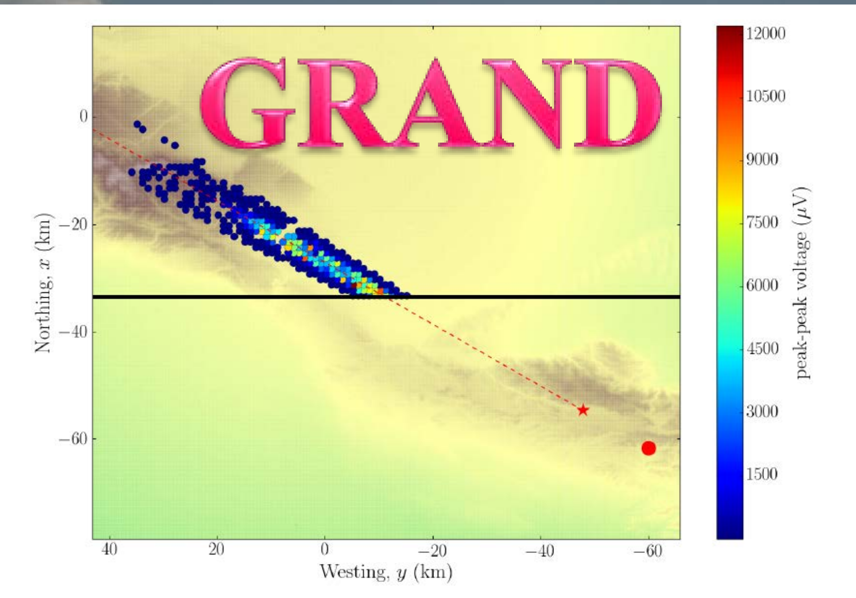
A.G. Vieregg, K. Bechtol, A. Romero-Wolf; JCAP 1602 (2016) no.02, 005



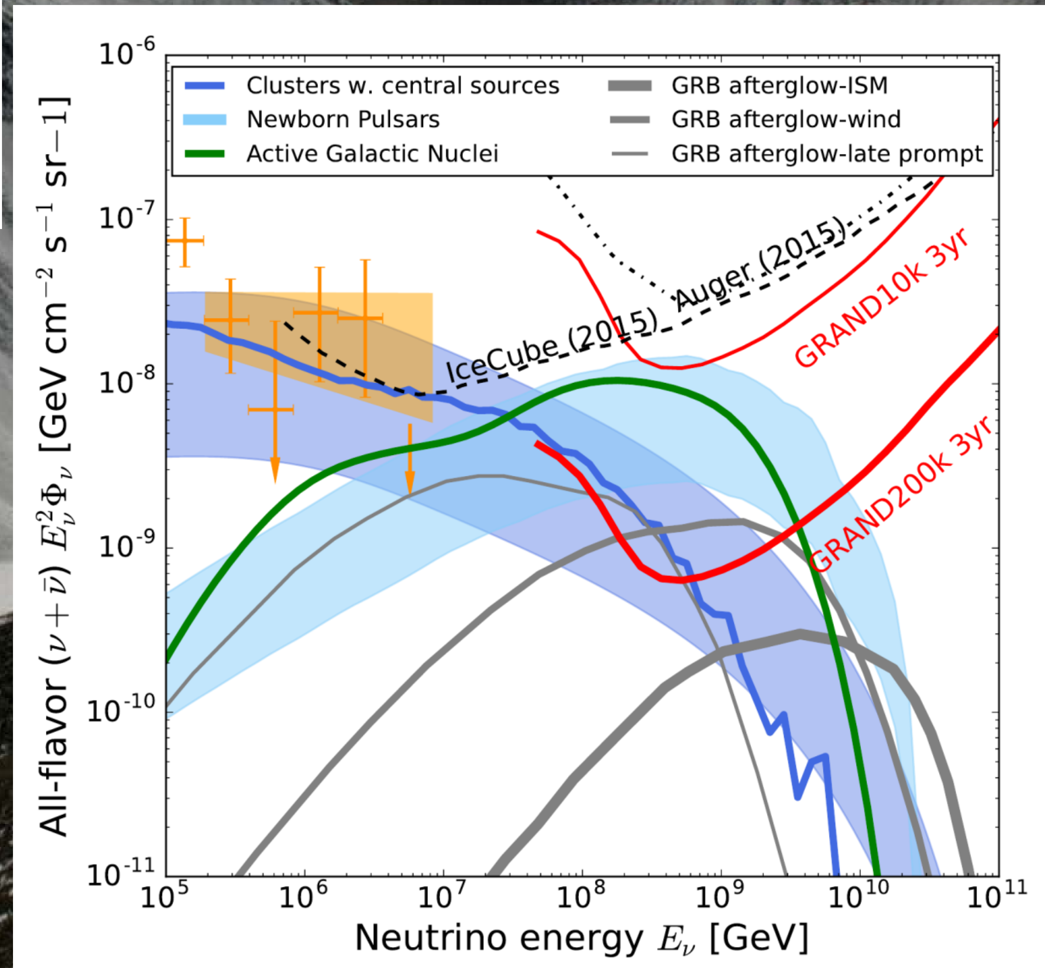




Grand35 (2.4 km^2) 2018
Grand300 (135 km^2) 2020 $10^{16.5}$-10^{18}eV
Grand10K (10^4 km^2) 2025
Grand200K (2 10^5 km^2) 2035?

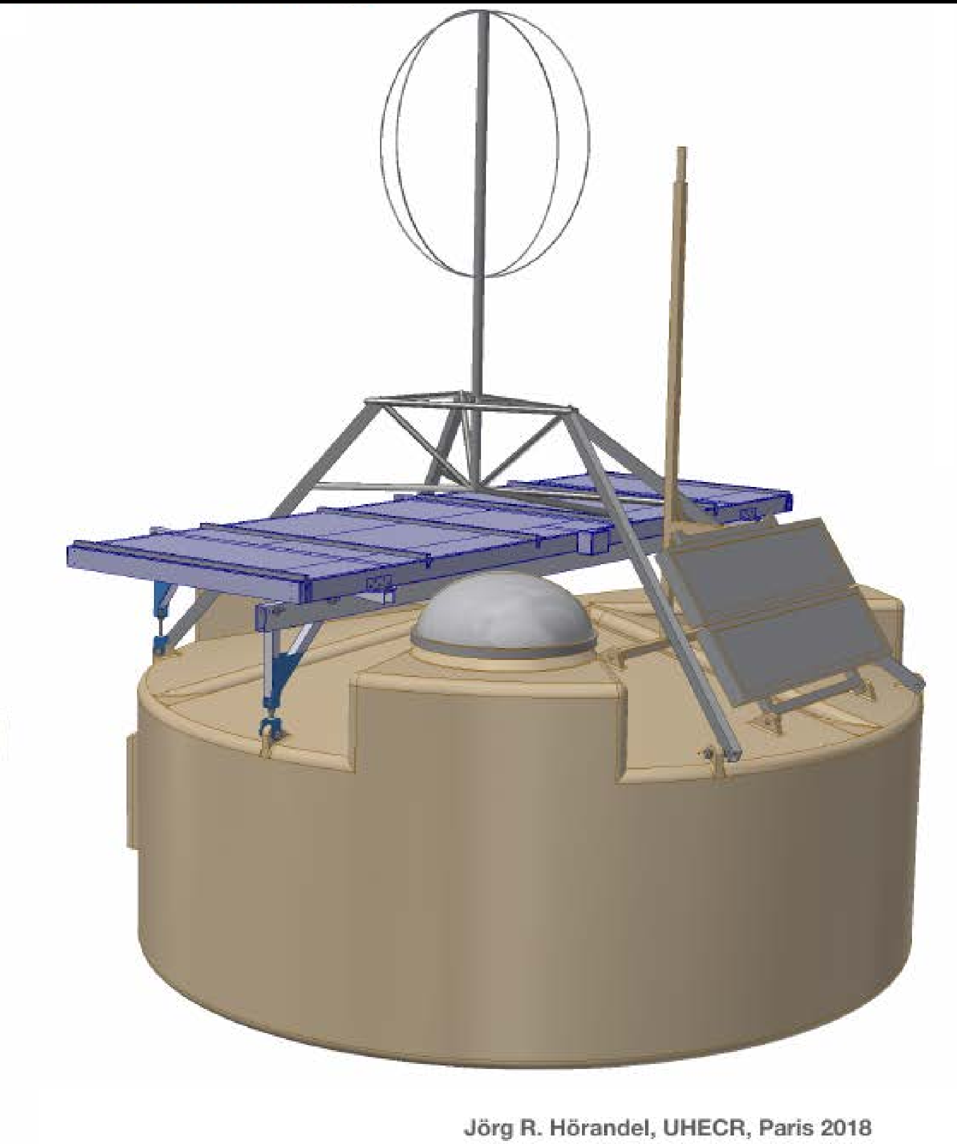


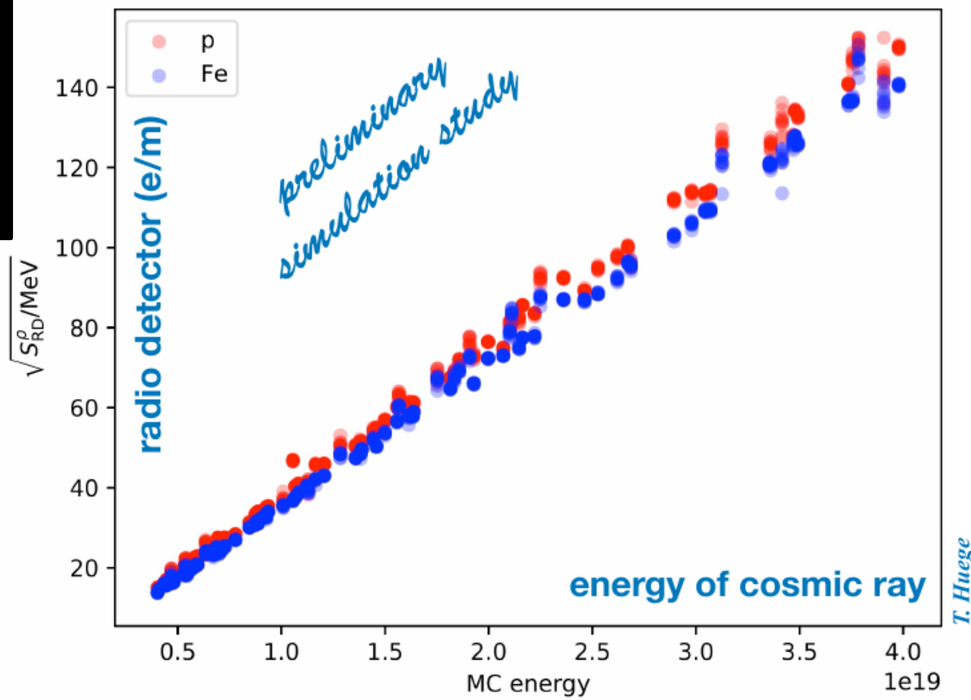
J. Alvarez-Muñiz et al ArXiv:1810.09994

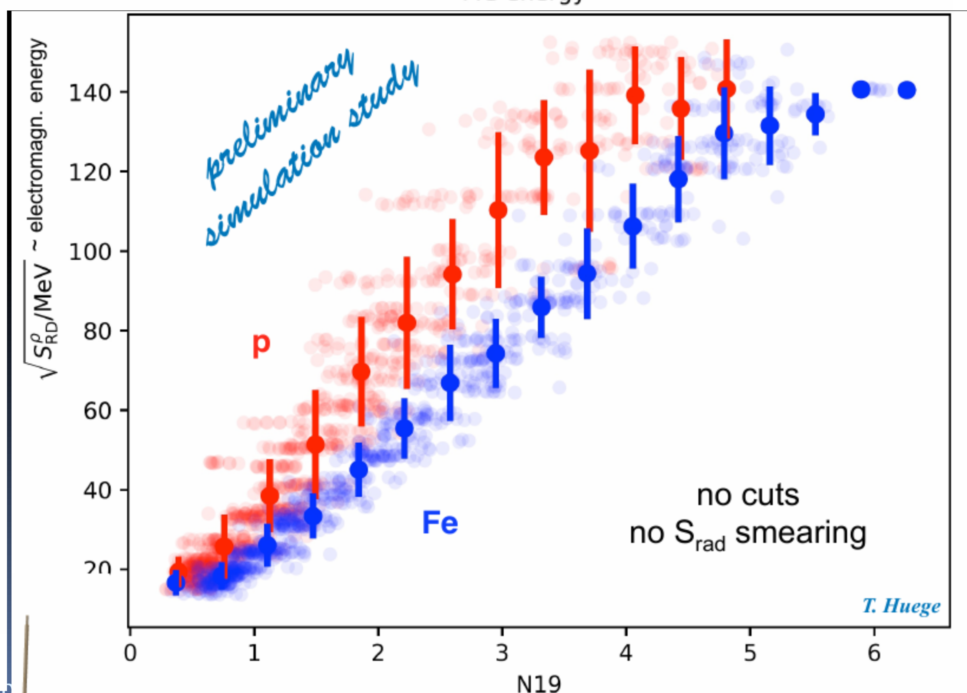


Auger Radio

J.Hörandel UHECR, Paris 2018







There has been much progress in radio

Many initiatives are being pursued explored

Ambitious plans targeting physics are quite advanced

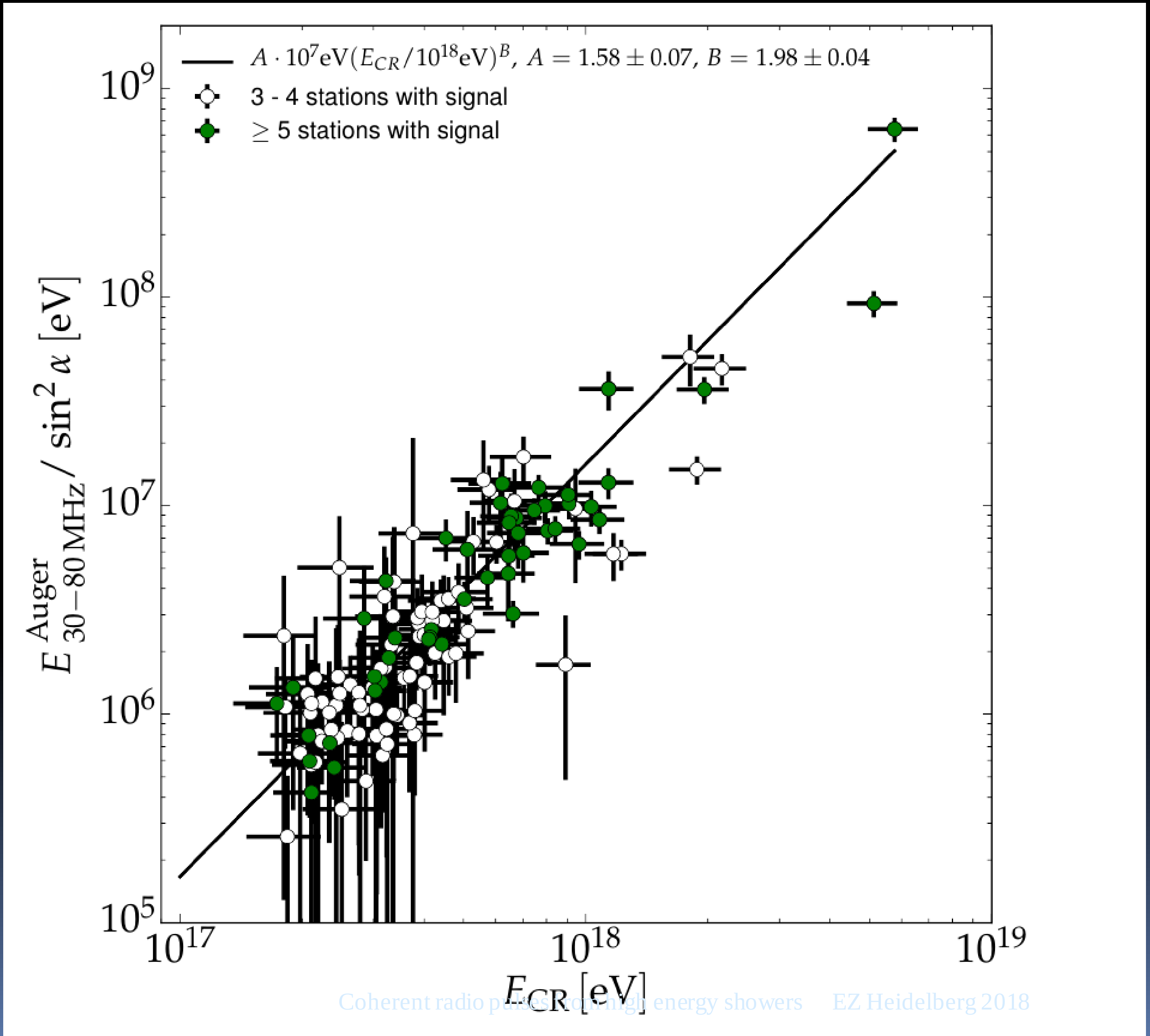
Surely new ones are bound to crop up

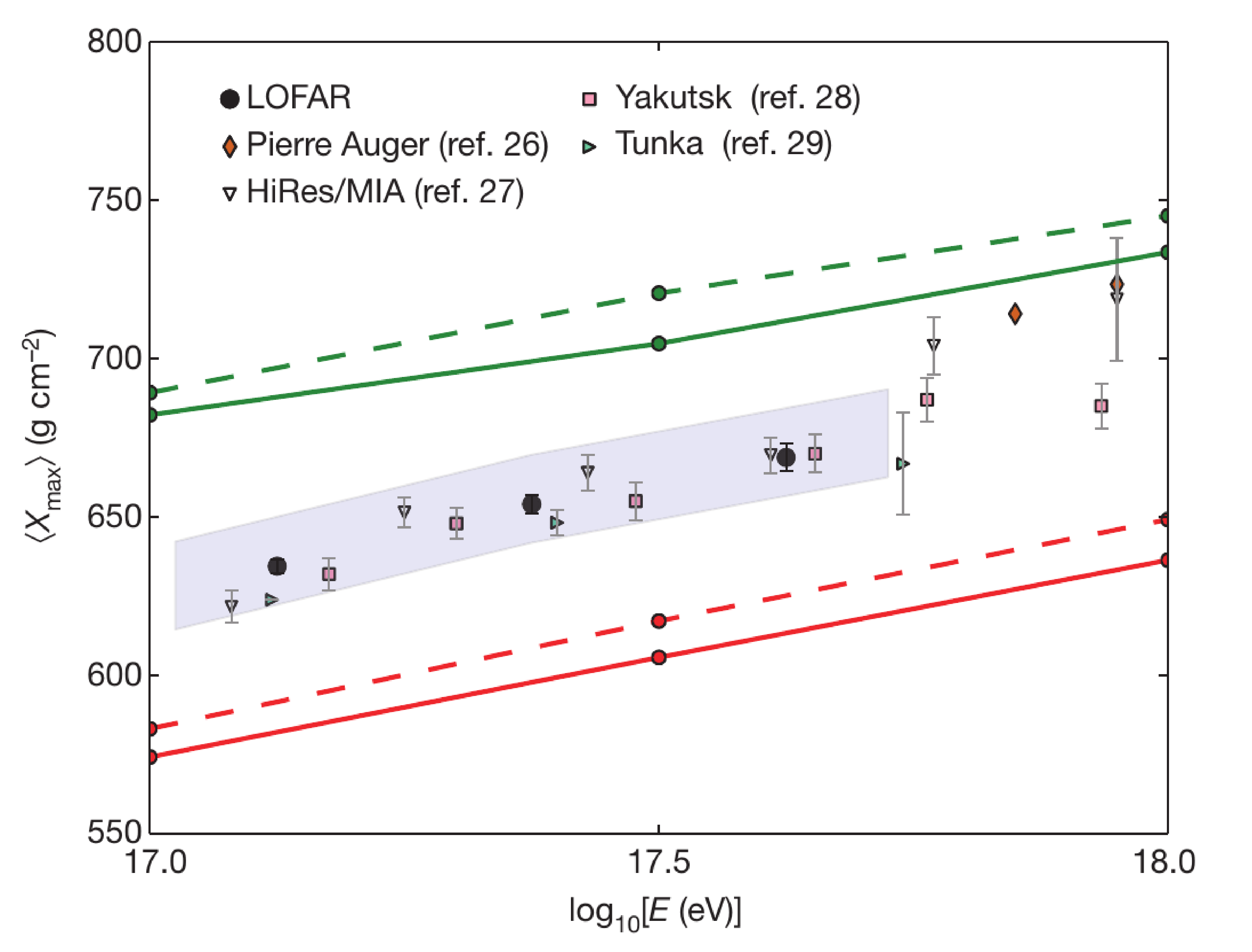
The future is wide open

Thank You

What have we been looking for?

Energy in radio correlated with shower energy



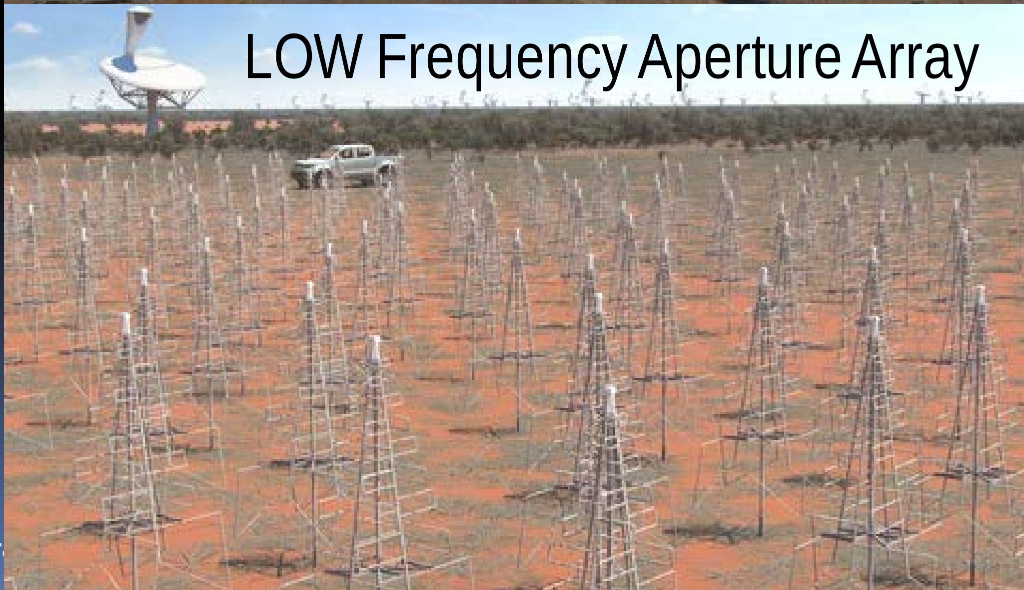


800
750
700
650
600
550
17.0
17.5
18.0
LOFAR
Pierre Auger (ref. 26)
HiRes/MIA (ref. 27)
Yakutsk (ref. 28)
Tunka (ref. 29)
$\langle X_{max} \rangle$ (g cm^{-2})
$\log_{10}[E$ (eV)]

SKA

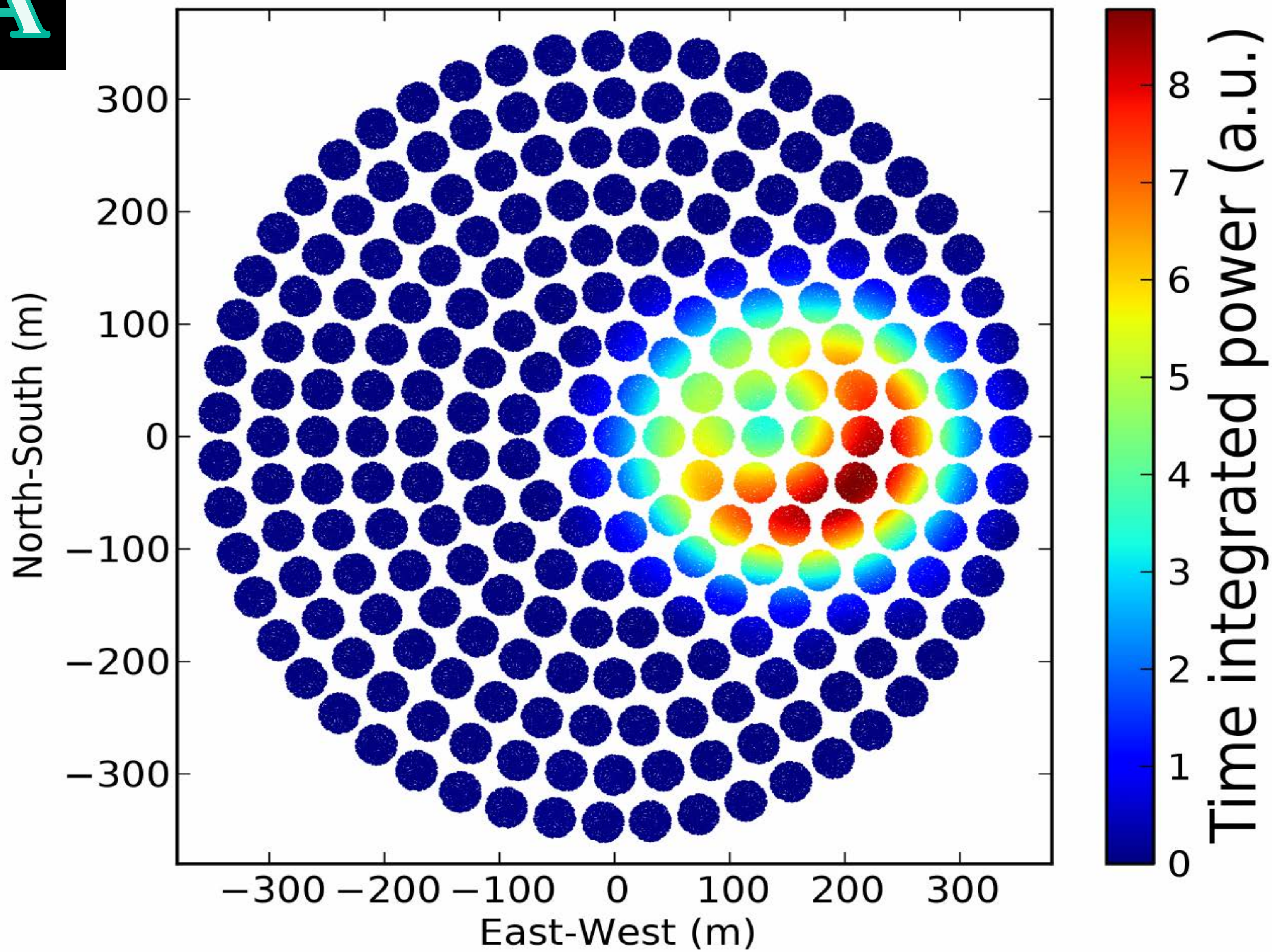
(Square Kilometer Array)

- world's largest radio telescope
  - 1 km^2 of total collecting area
  - thousands of antennas
  - to be built in Australia & South Africa
- broad scientific goals: astronomical & cosmological obs.
- "phased array": can observe multiple regions of sky simultaneously !!
- Moon proposed to be observed at different frequency bands:
  - SKA-LOW (100 – 750 MHz)
  - SKA-MID (350 – 1760 MHz)
- can also detect UHECRs



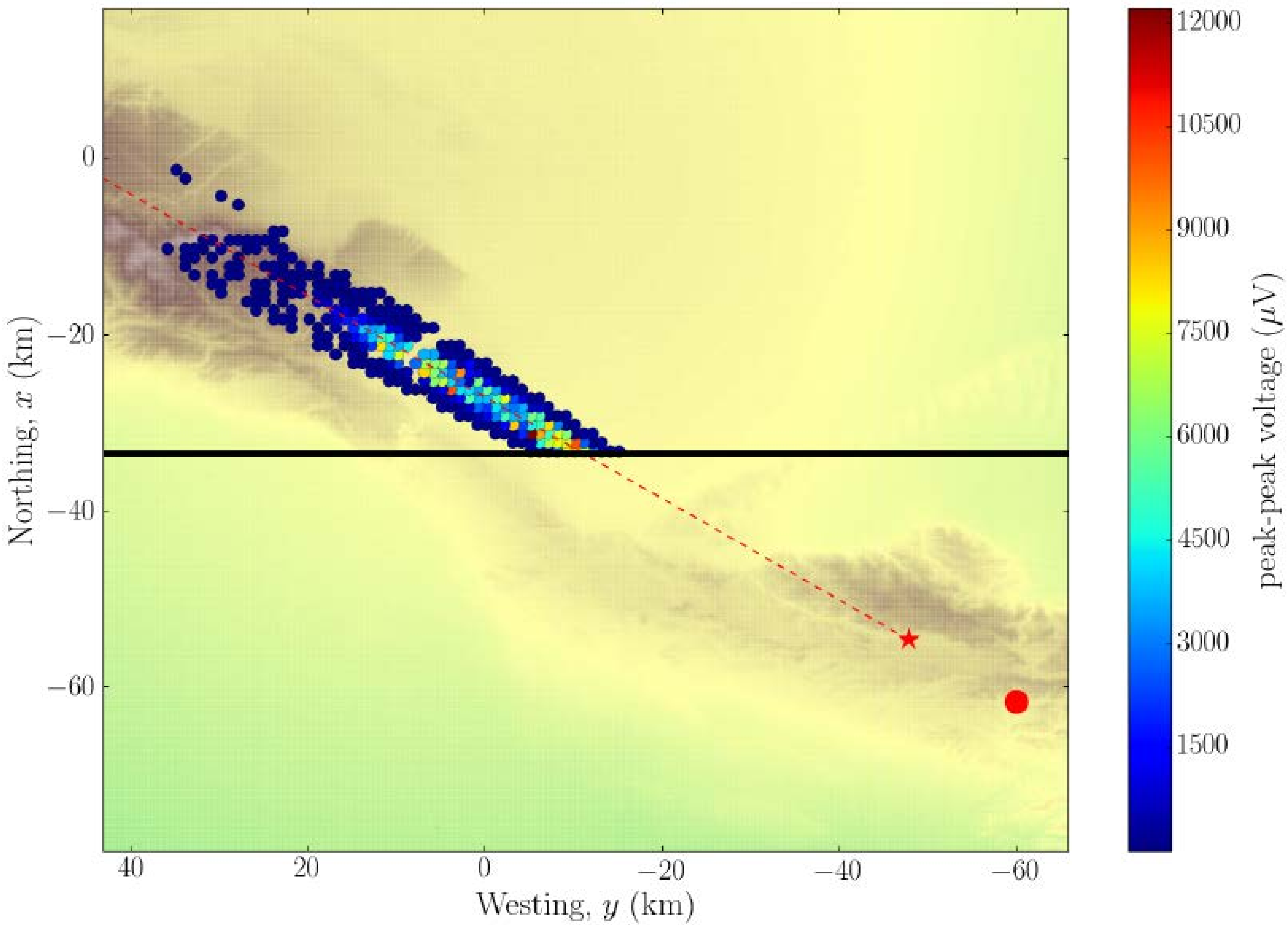
Coherent r

SKA

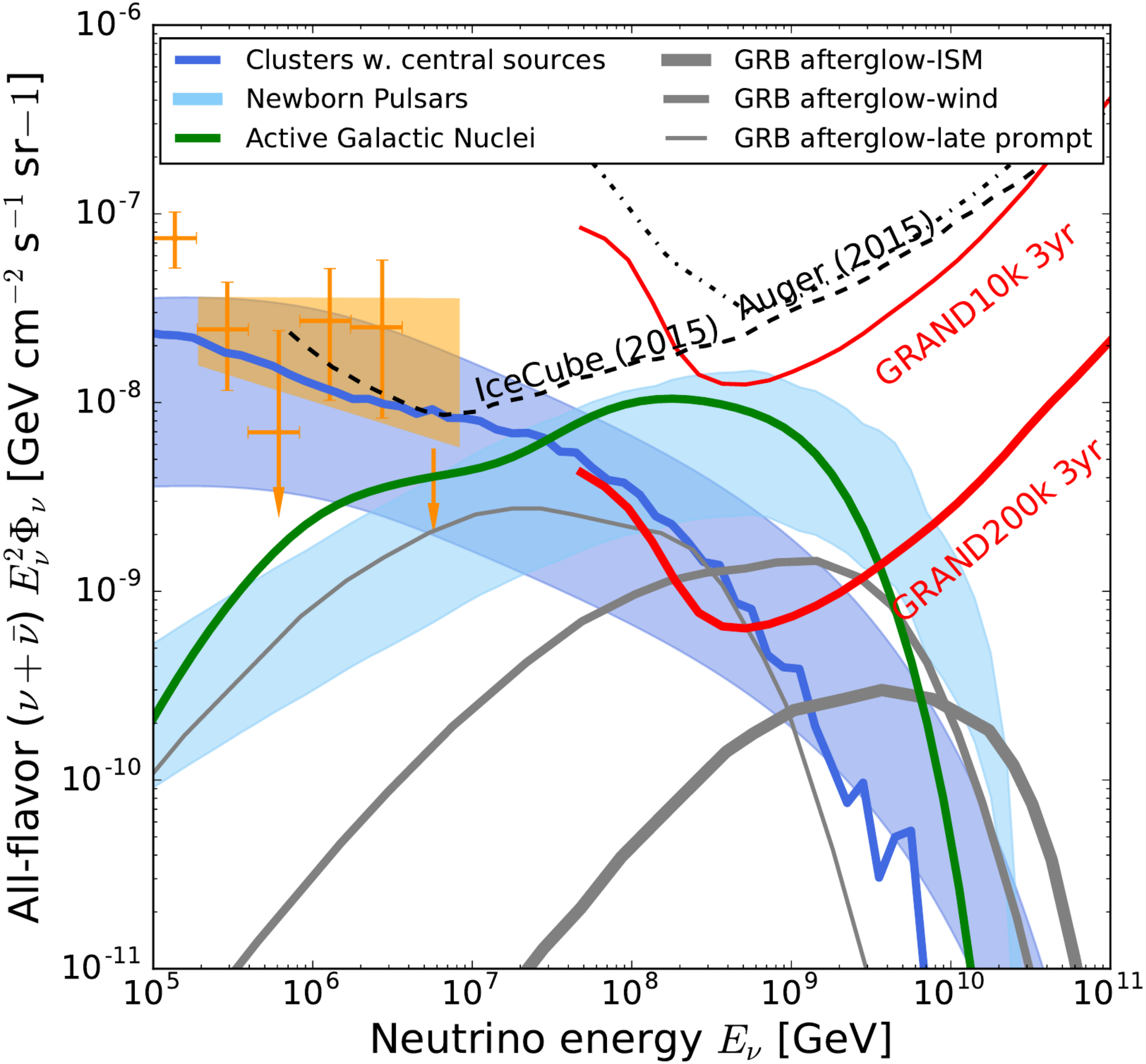


North-South (m)
East-West (m)
Time integrated power (a.u.)
300
200
100
0
−100
−200
−300
−300 −200 −100 0 100 200 300
0 1 2 3 4 5 6 7 8

GRAND TREND

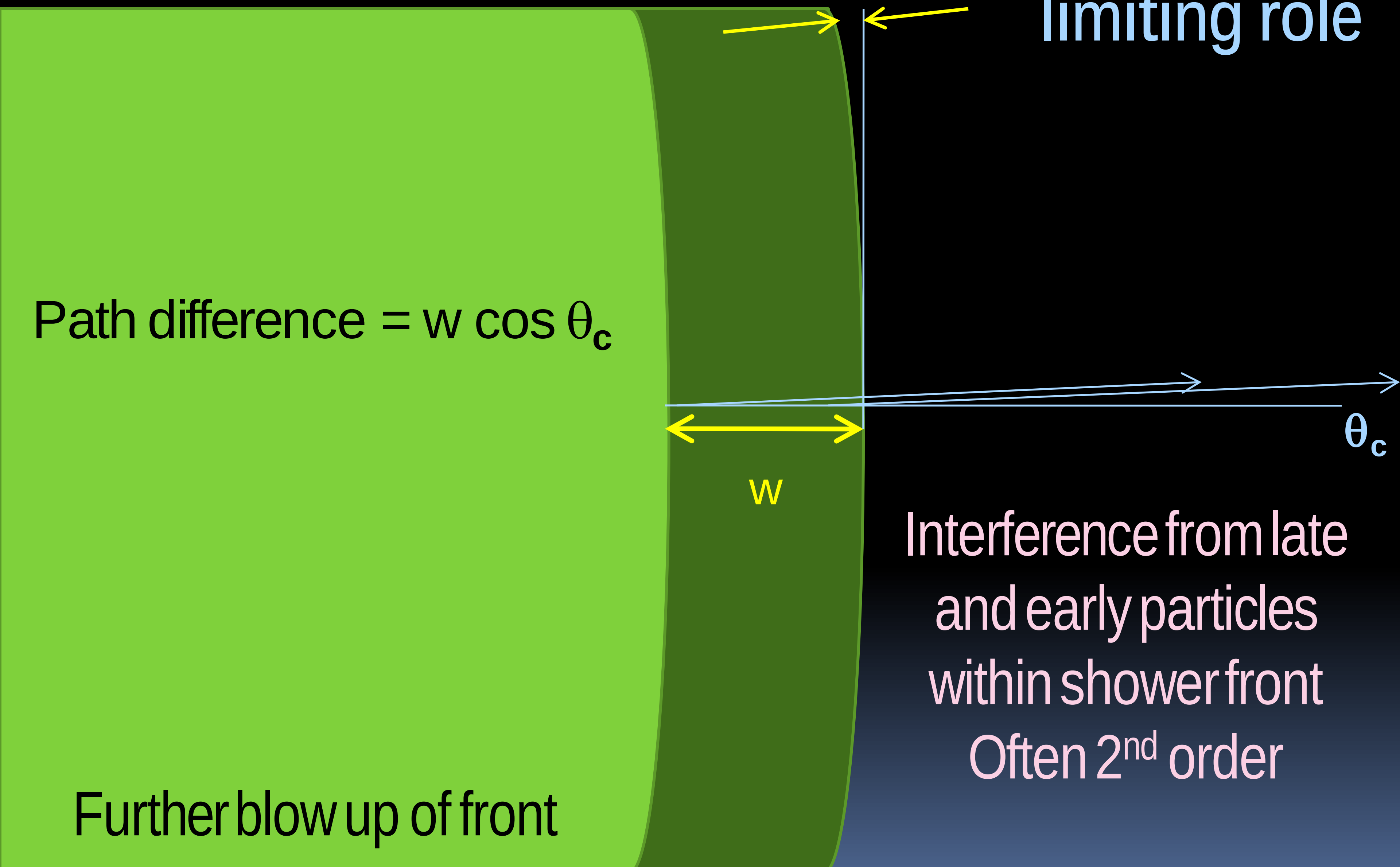


0
−20
−40
−60
Northing, x (km)
40
20
0
−20
−40
−60
Westing, y (km)
12000
10500
9000
7500
6000
4500
3000
1500
peak-peak voltage (μV)


Clusters w. central sources
Newborn Pulsars
Active Galactic Nuclei
GRB afterglow-ISM
GRB afterglow-wind
GRB afterglow-late prompt
IceCube (2015)
Auger (2015)
GRAND10k 3yr
GRAND200k 3yr
All-flavor $(\nu+\bar{\nu})$ $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr-1]
Neutrino energy E_ν [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}

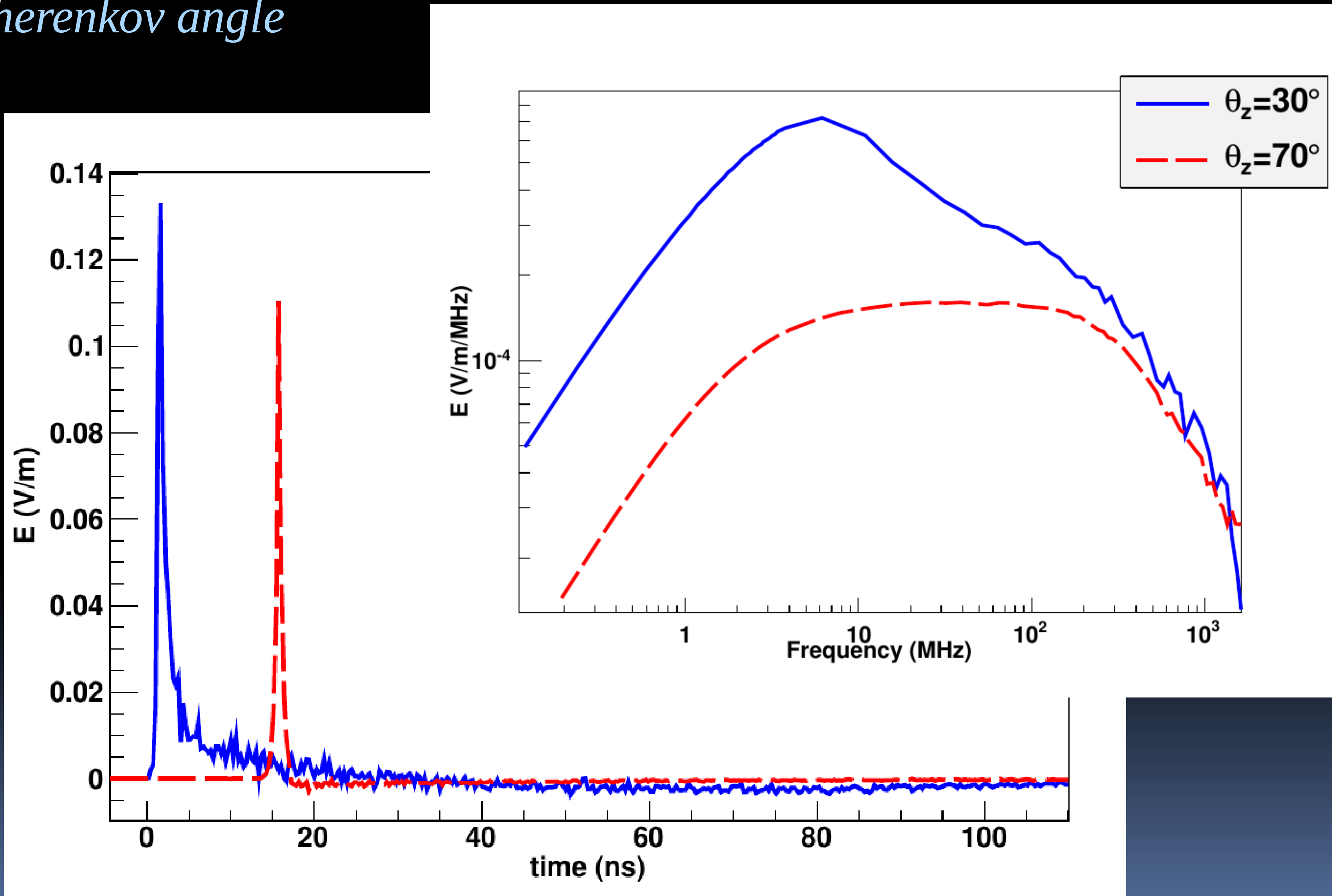
Why is the atmosphere so different?

Shower front thickness and curvature play the limiting role

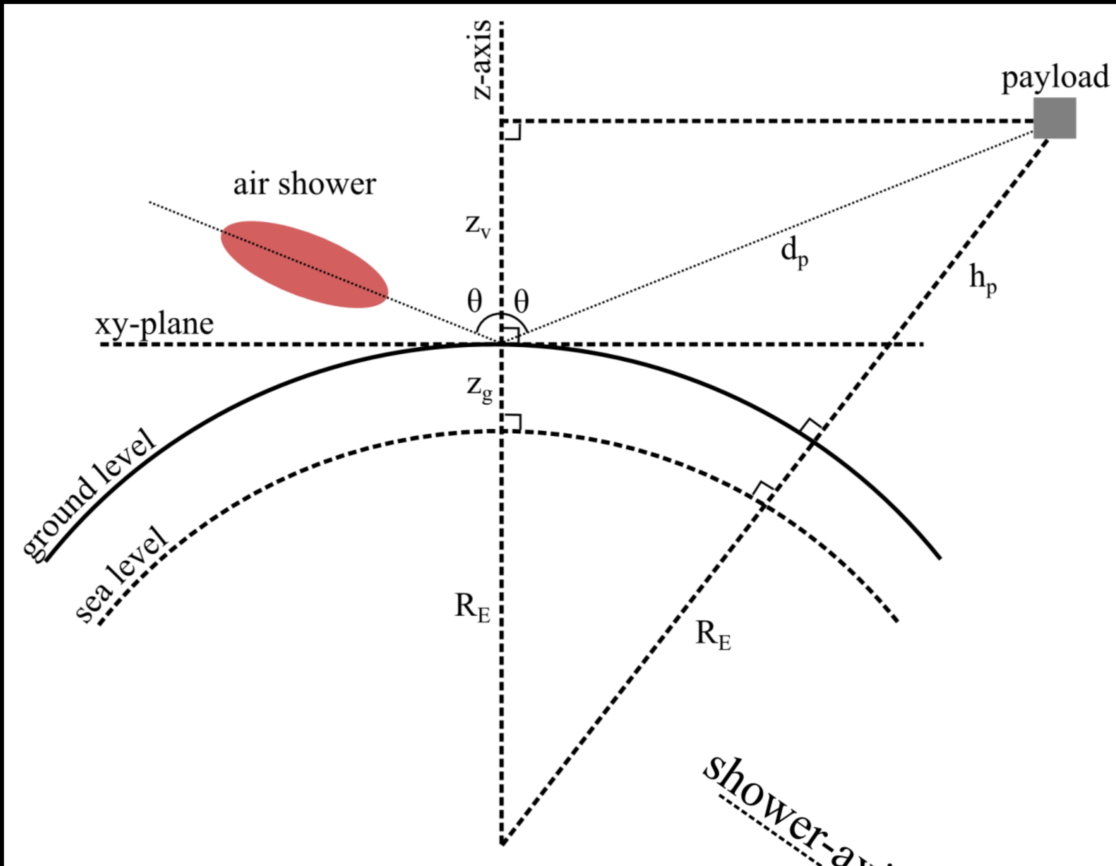


Interference from late and early particles within shower front
Often 2nd order

proton shower of energy 10^{19} eV in Antarctica at Cherenkov angle

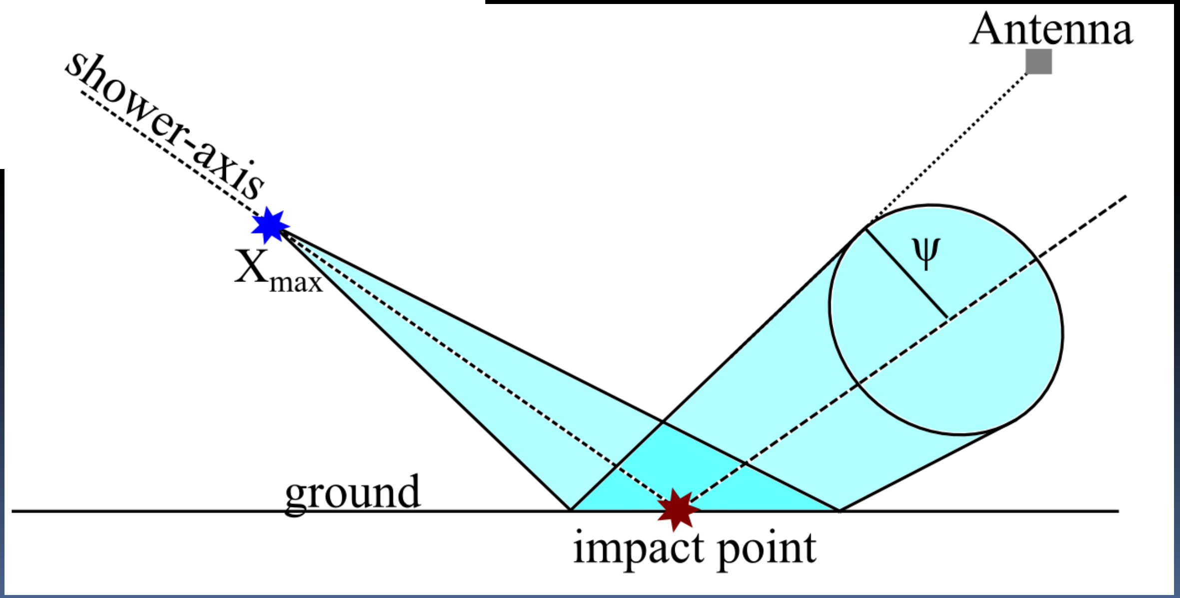


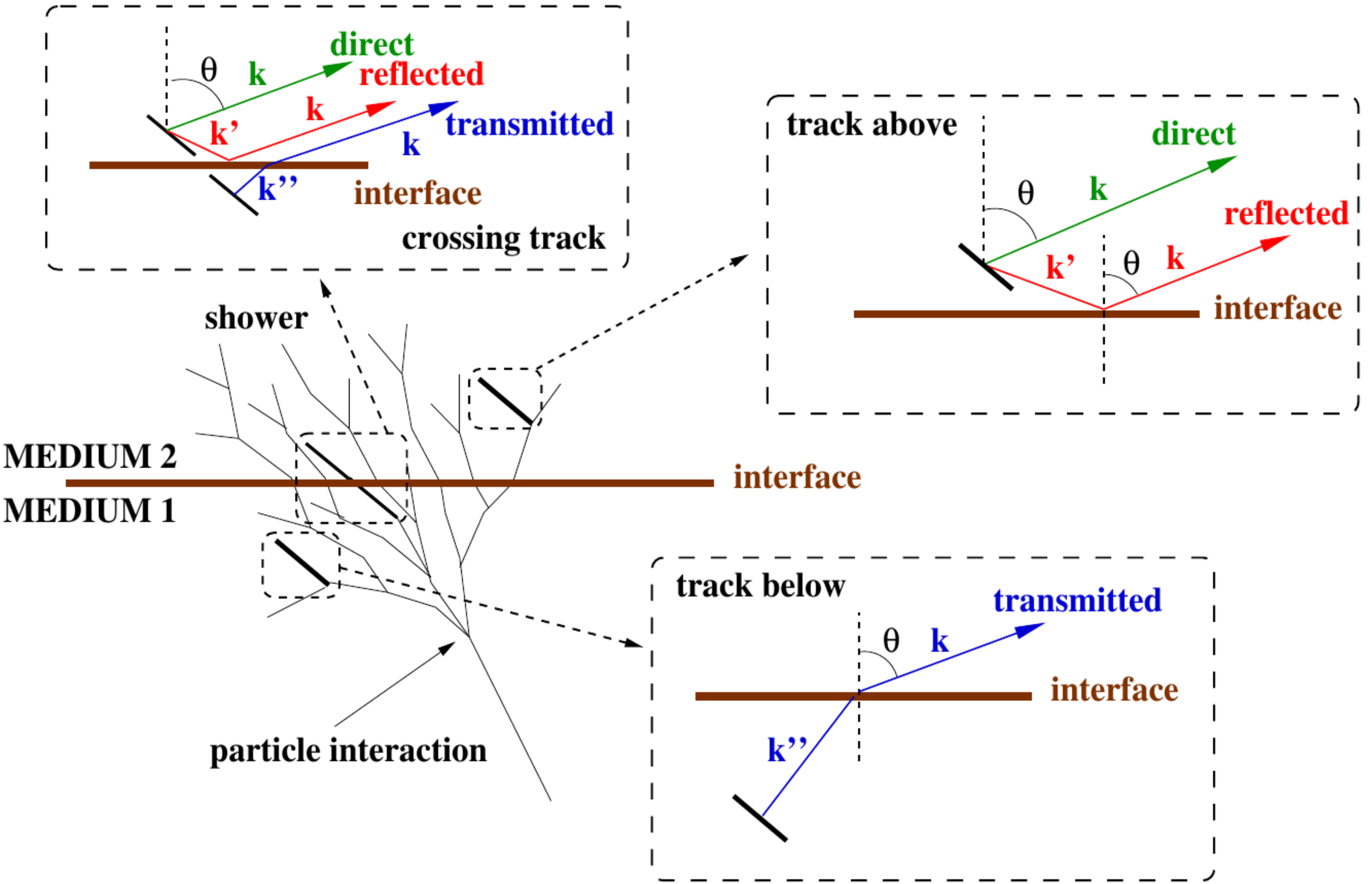
Is the picture Complete?



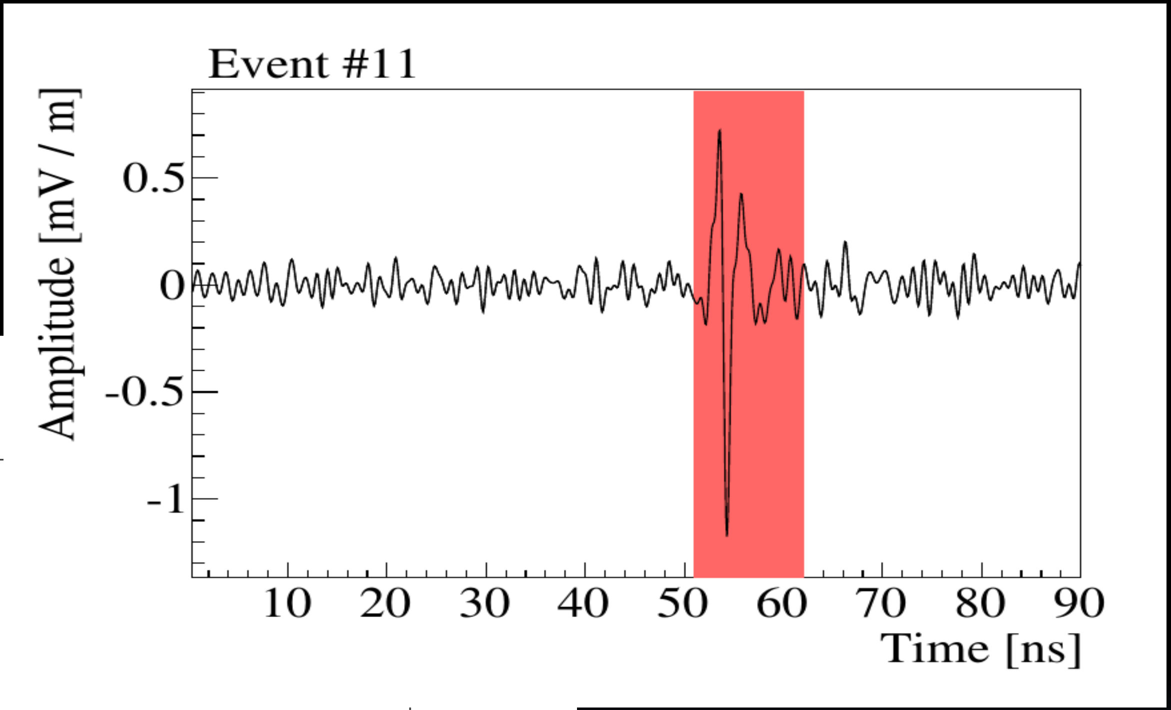
Reflection
- Earth's curvature
- Roughness

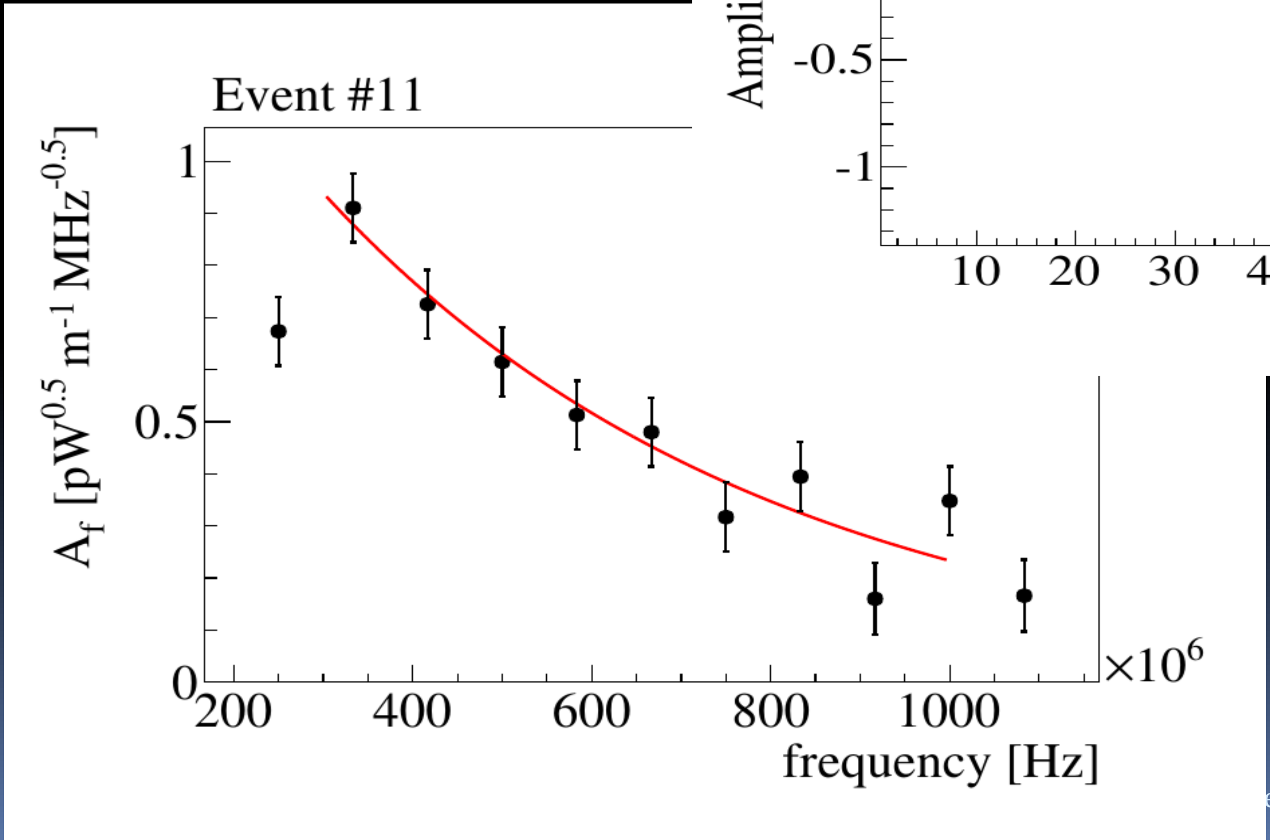
Refractive Index
- Ray's curvature
- Variability

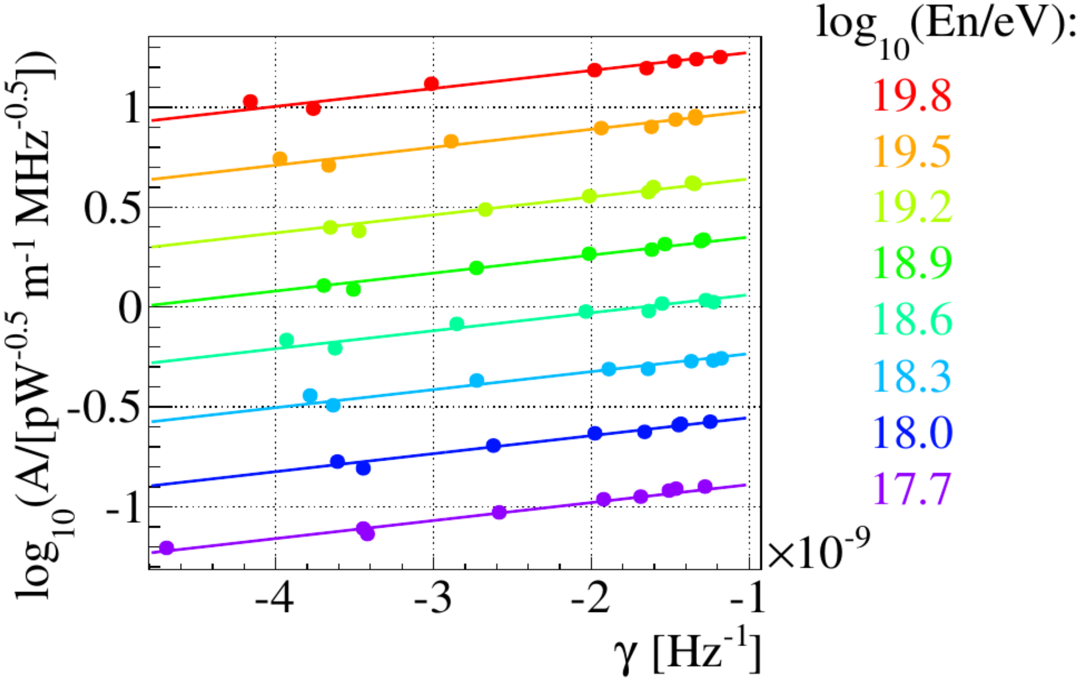


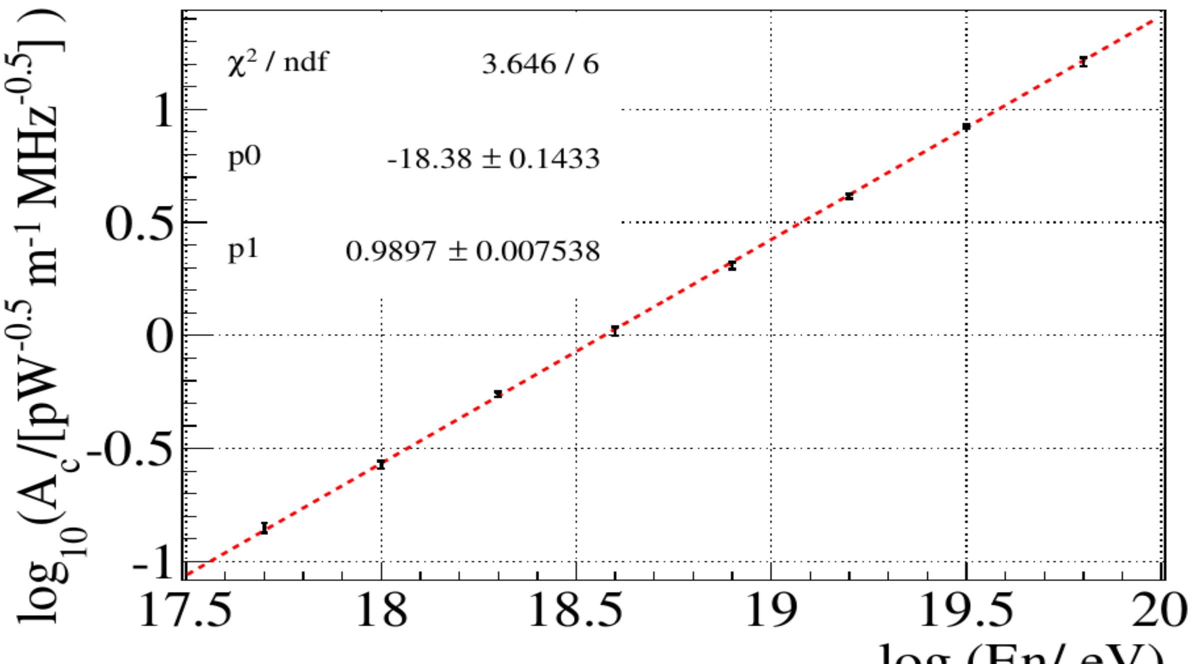

direct
θ
k
reflected
k
k'
transmitted
k
k''
interface
crossing track
track above
direct
θ
k
reflected
k'
θ
k
interface
shower
MEDIUM 2
interface
MEDIUM 1
track below
transmitted
θ
k
interface
k''
particle interaction

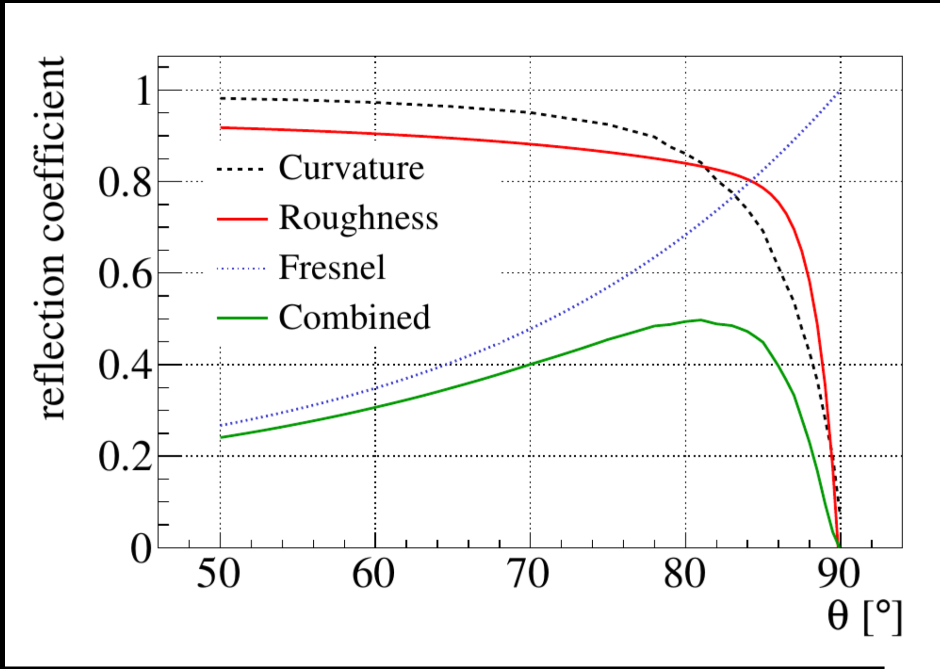
Events can be reconstructed from single location!!



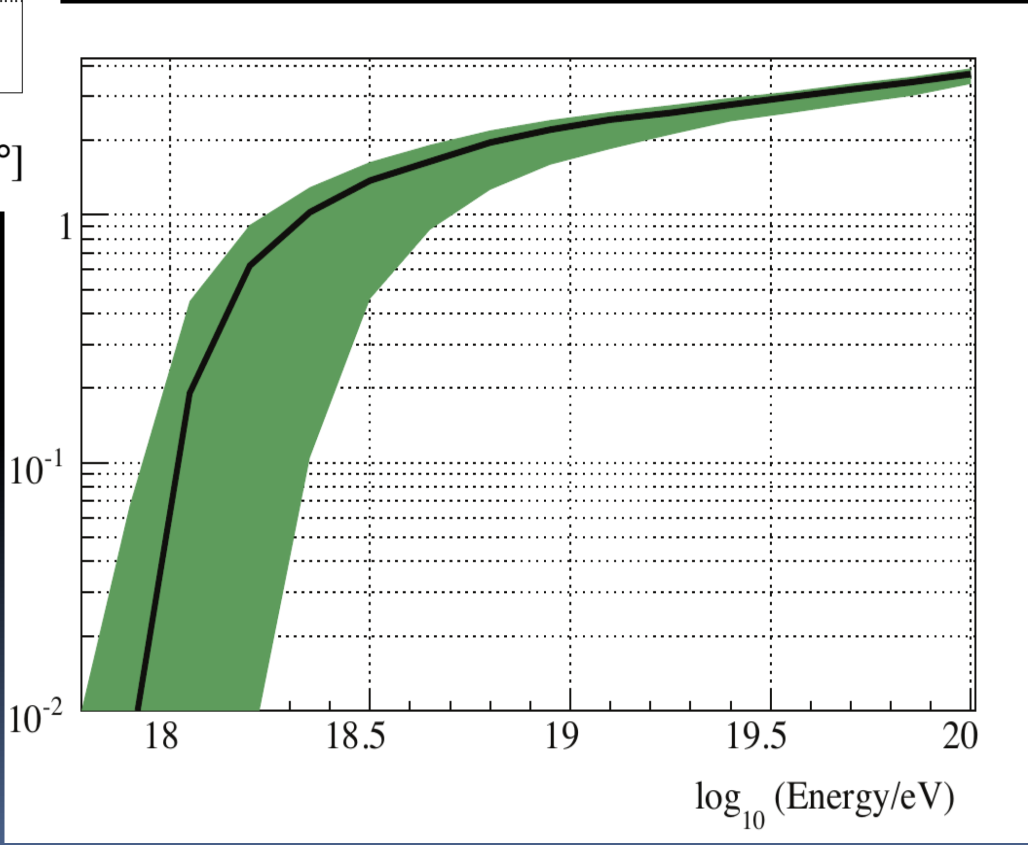



log10(En/eV):
19.8
19.5
19.2
18.9
18.6
18.3
18.0
17.7
log10(A/[pW^-0.5 m^-1 MHz^-0.5])
γ [Hz^-1]
×10^-9

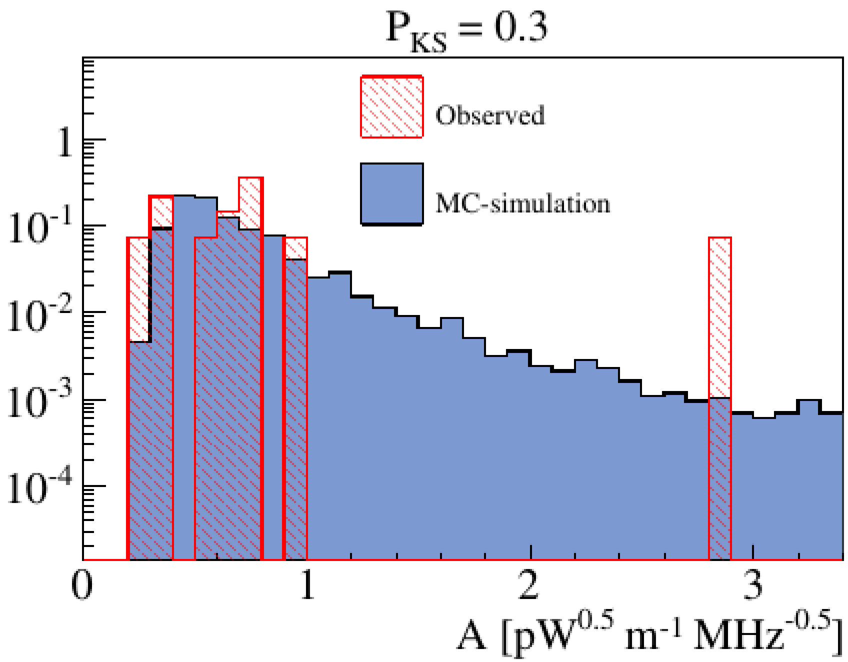

χ² / ndf 3.646 / 6
p0 -18.38 ± 0.1433
p1 0.9897 ± 0.007538
log10(Ac/[pW^-0.5 m^-1 MHz^-0.5])
log (En/ eV)

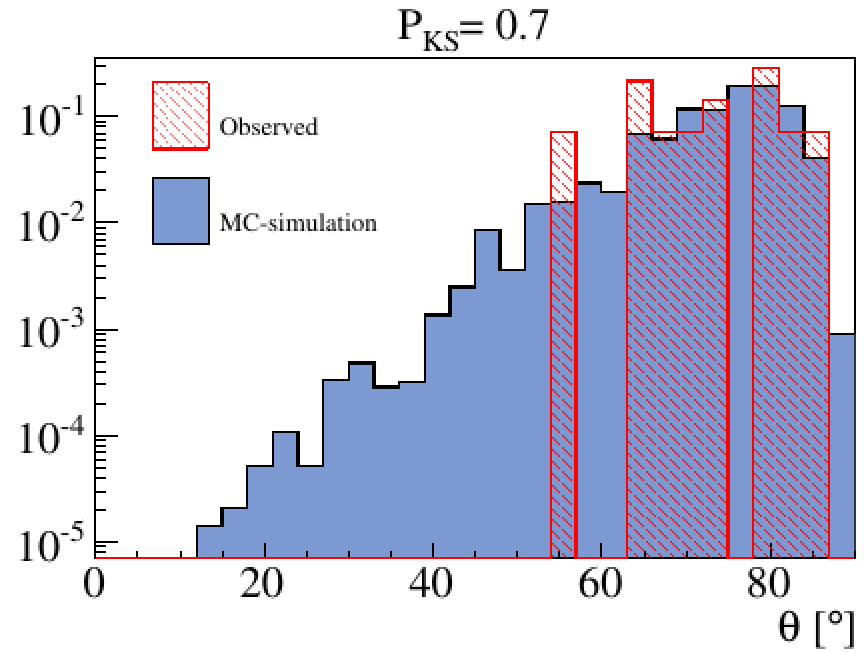


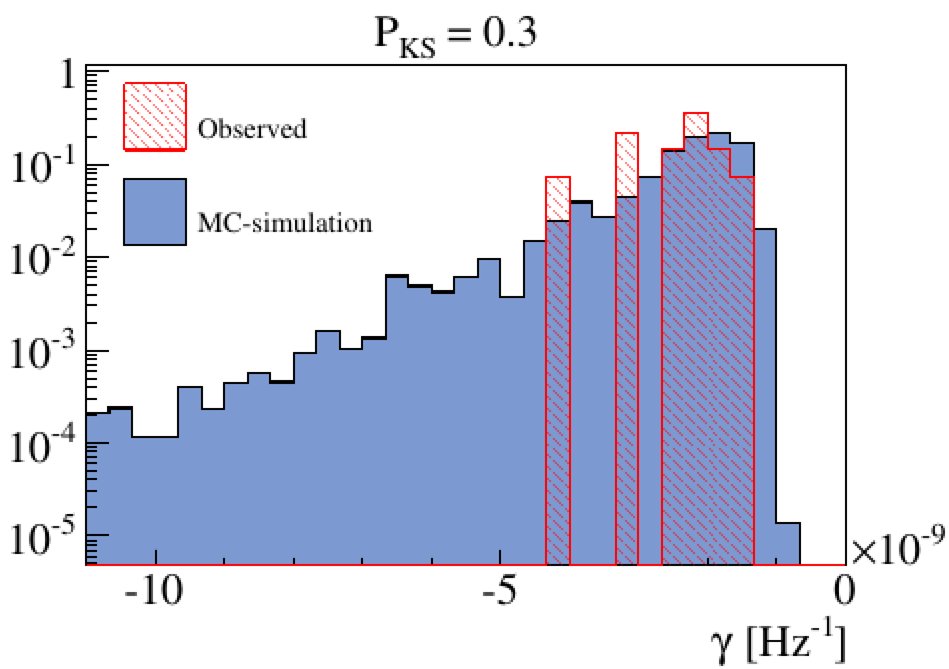
reflection coefficient
1
0.8
0.6
0.4
0.2
0
50
60
70
80
90
θ [°]
Curvature
Roughness
Fresnel
Combined

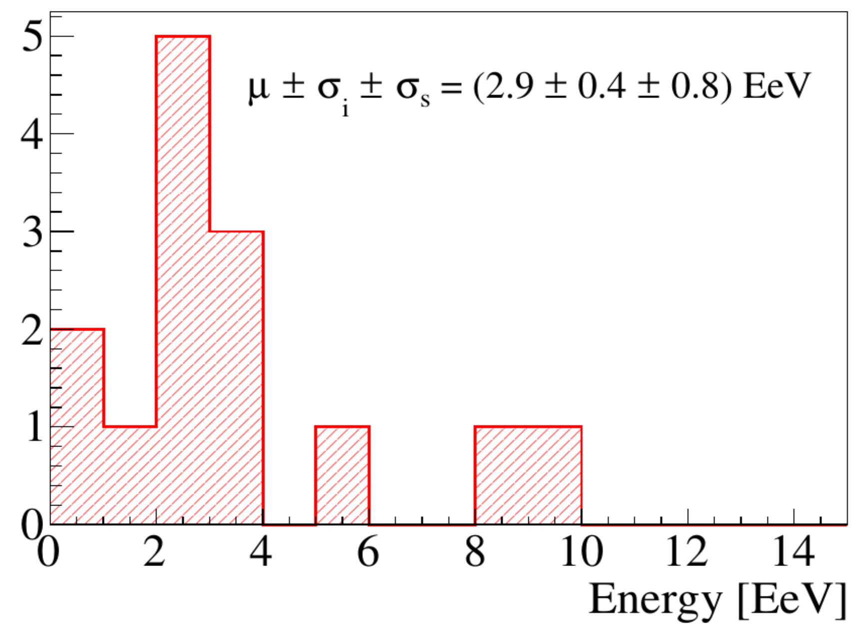


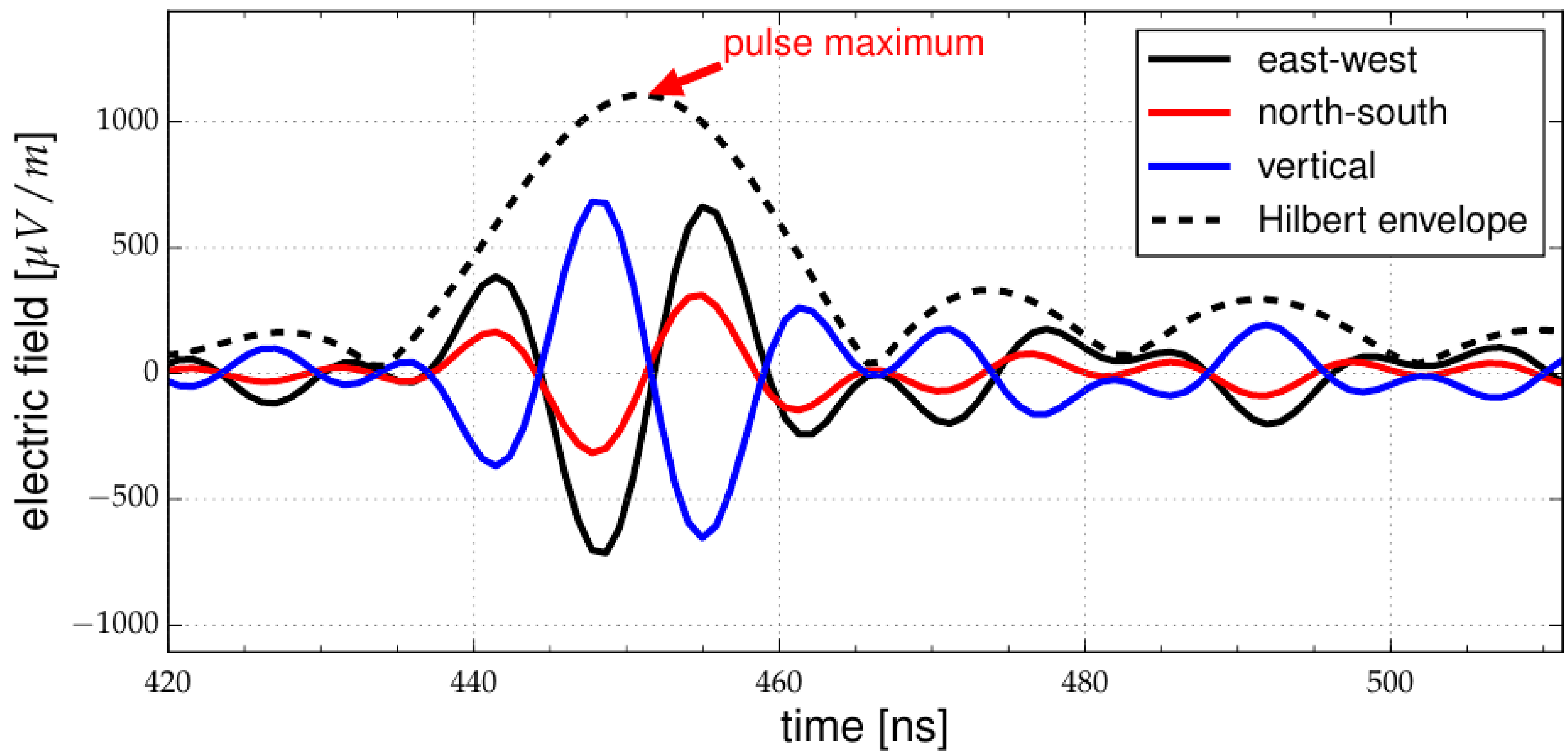
1
10^{-1}
10^{-2}
18
18.5
19
19.5
20
$\log_{10}$ (Energy/eV)


$P_{KS} = 0.3$
Observed
MC-simulation
A [pW$^{0.5}$ m^{-1} MHz$^{-0.5}$]

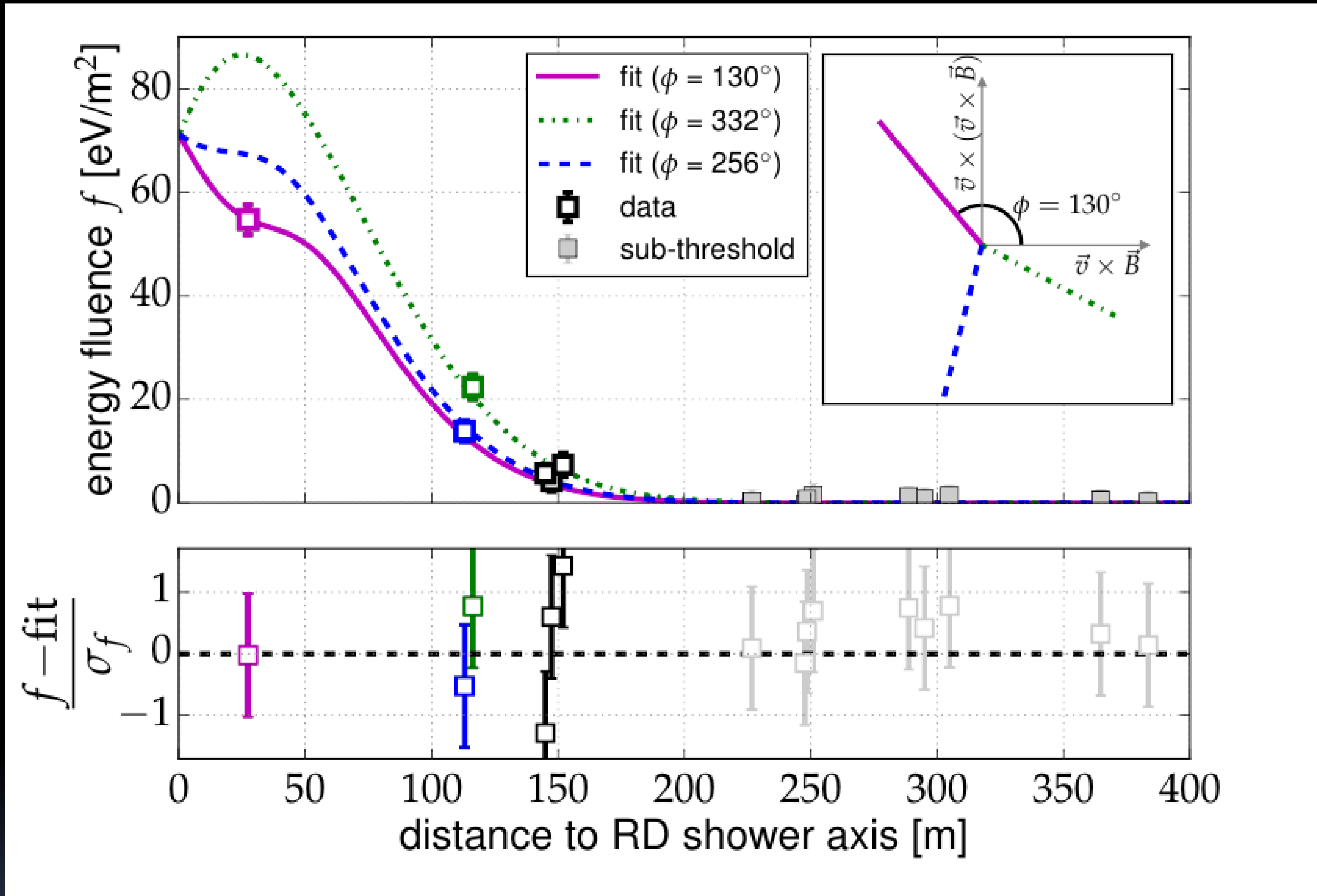

$P_{KS} = 0.7$
Observed
MC-simulation
θ [°]


$P_{KS} = 0.3$
Observed
MC-simulation
×10^{-9}
γ [Hz^{-1}]

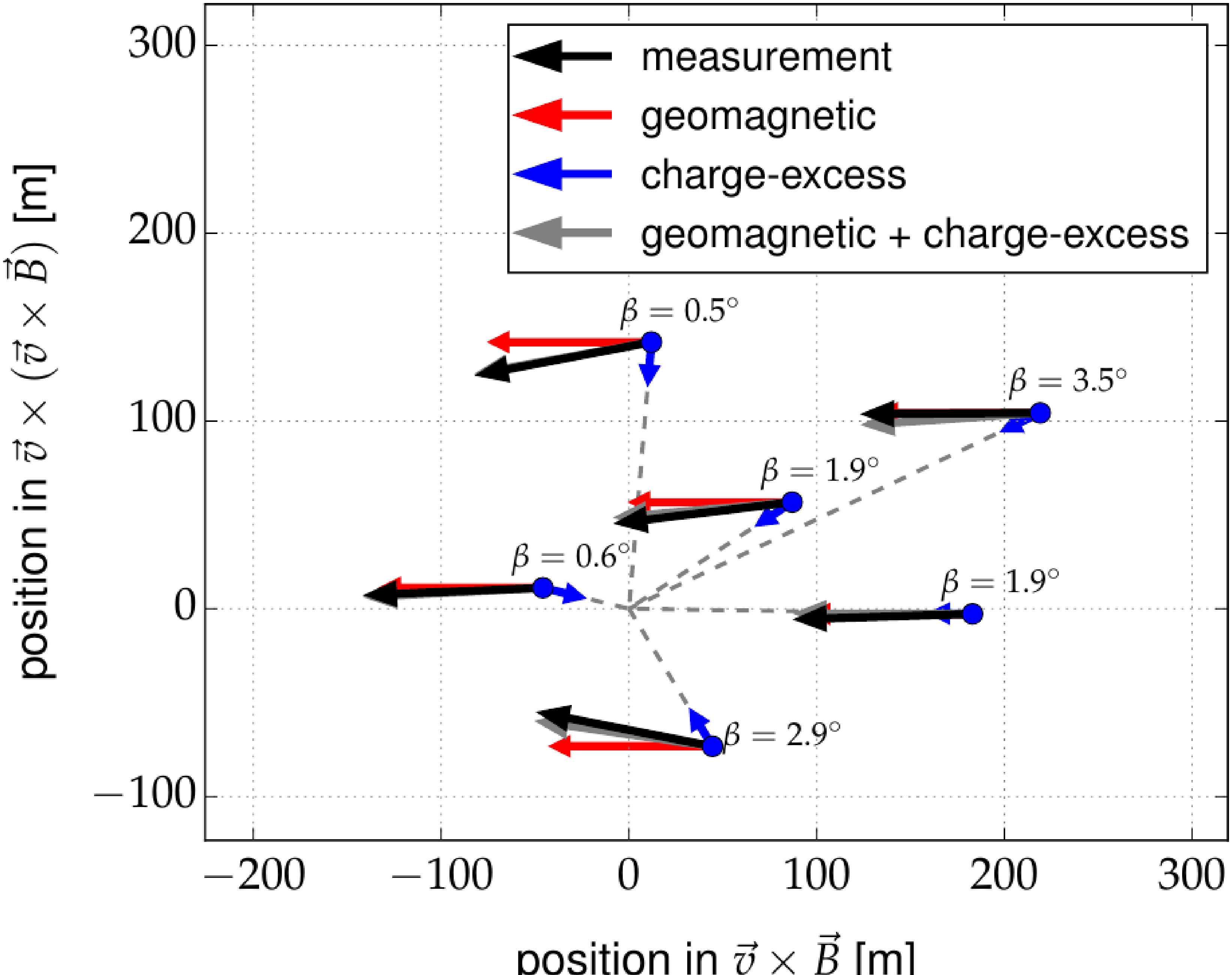

$\mu \pm \sigma_i \pm \sigma_s = (2.9 \pm 0.4 \pm 0.8)$ EeV
Energy [EeV]

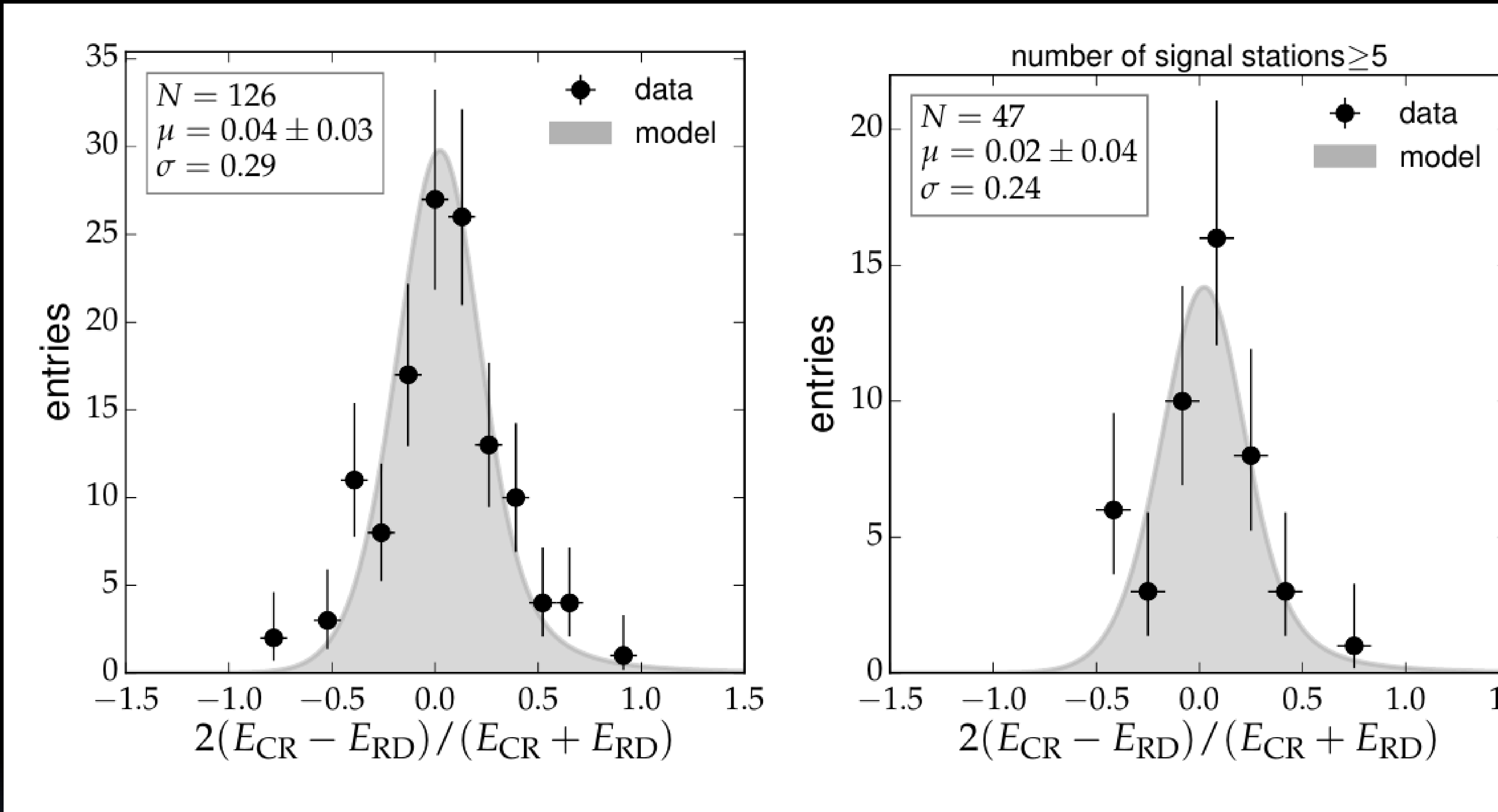


pulse maximum
east-west
north-south
vertical
Hilbert envelope
electric field [$\mu V / m$]
1000
500
0
−500
−1000
420
440
460
480
500
time [ns]



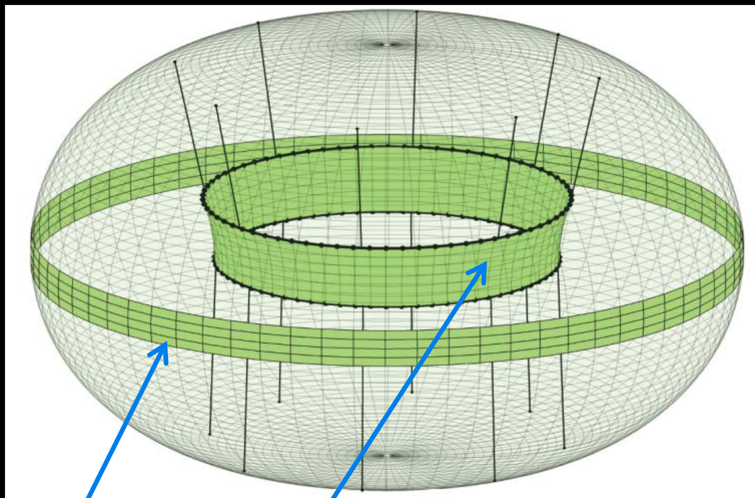
fit (ϕ = 130°)
fit (ϕ = 332°)
fit (ϕ = 256°)
data
sub-threshold
ϕ = 130°
energy fluence f [eV/m²]
0
20
40
60
80
f − fit / σ_f
1
0
−1
0
50
100
150
200
250
300
350
400
distance to RD shower axis [m]


measurement
geomagnetic
charge-excess
geomagnetic + charge-excess
$\beta = 0.5^\circ$
$\beta = 3.5^\circ$
$\beta = 1.9^\circ$
$\beta = 0.6^\circ$
$\beta = 1.9^\circ$
$\beta = 2.9^\circ$
300
200
100
0
−100
−200
−100
0
100
200
300
position in $\vec{v} \times (\vec{v} \times \vec{B})$ [m]
position in $\vec{v} \times \vec{B}$ [m]



$N = 126$
$\mu = 0.04 \pm 0.03$
$\sigma = 0.29$
data
model
entries
$2(E_{CR} - E_{RD})/(E_{CR} + E_{RD})$
number of signal stations≥5
$N = 47$
$\mu = 0.02 \pm 0.04$
$\sigma = 0.24$
data
model
entries
$2(E_{CR} - E_{RD})/(E_{CR} + E_{RD})$

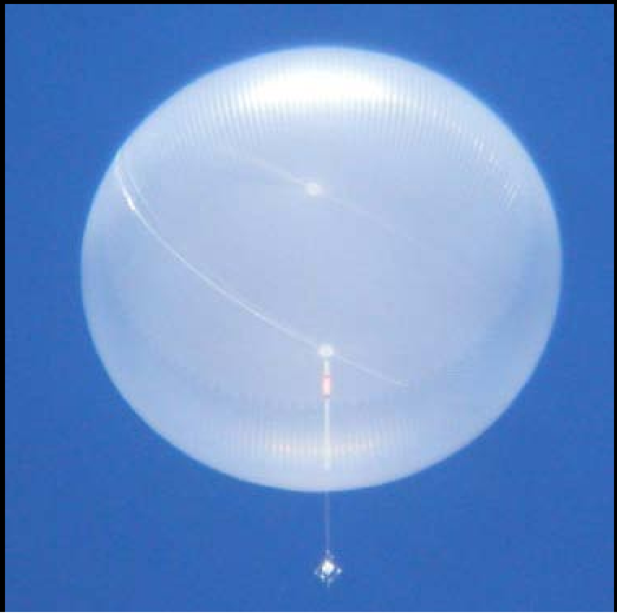
The future is wide open

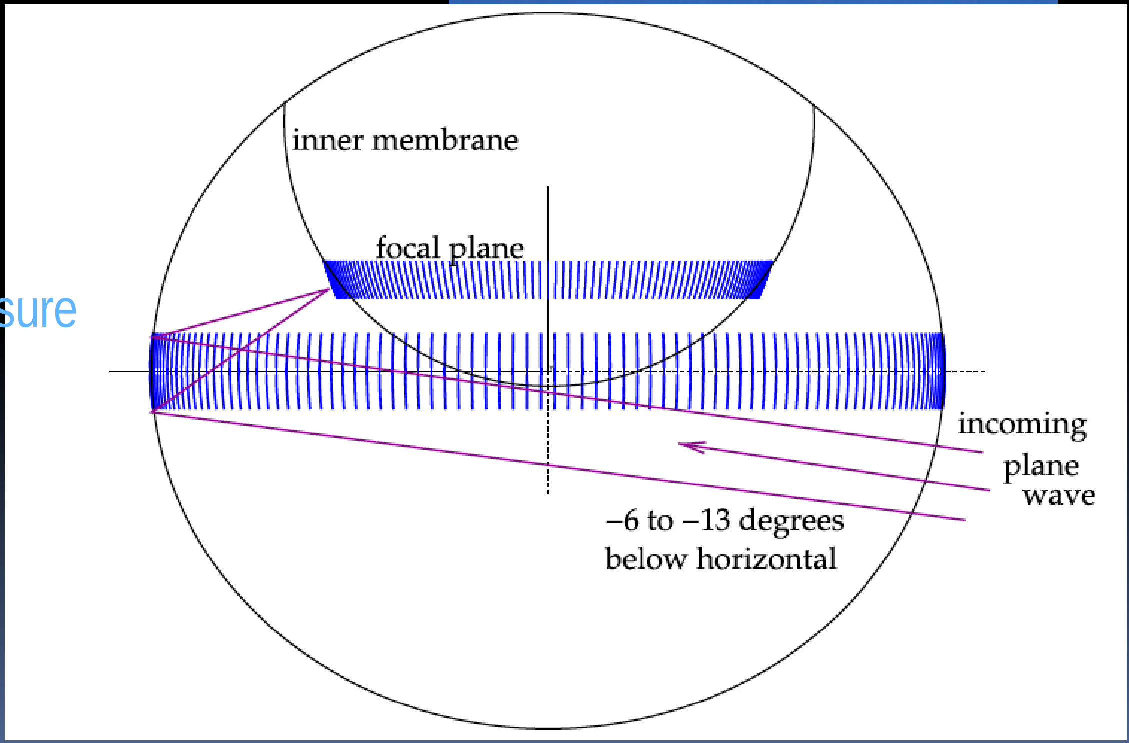


toroidal reflector

feed array @ focus

EVA





- Concept: Turn an entire super pressure balloon into the antenna !!

Similar sensitivity to full, 3 y of ground-based arrays

Gorham et al. APP 35, 242 (2011)

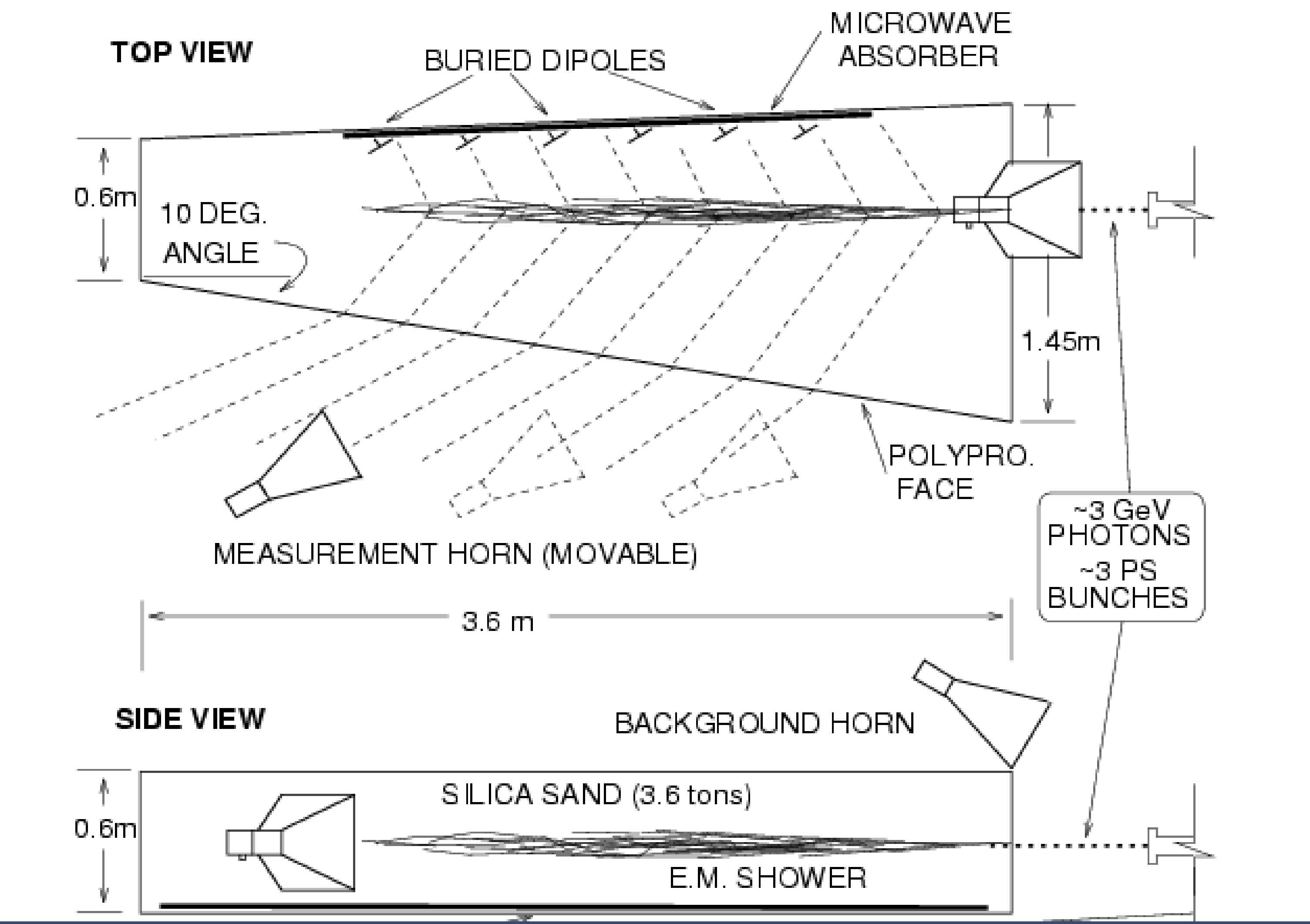
?

Coherent radio detection: ν-experiments

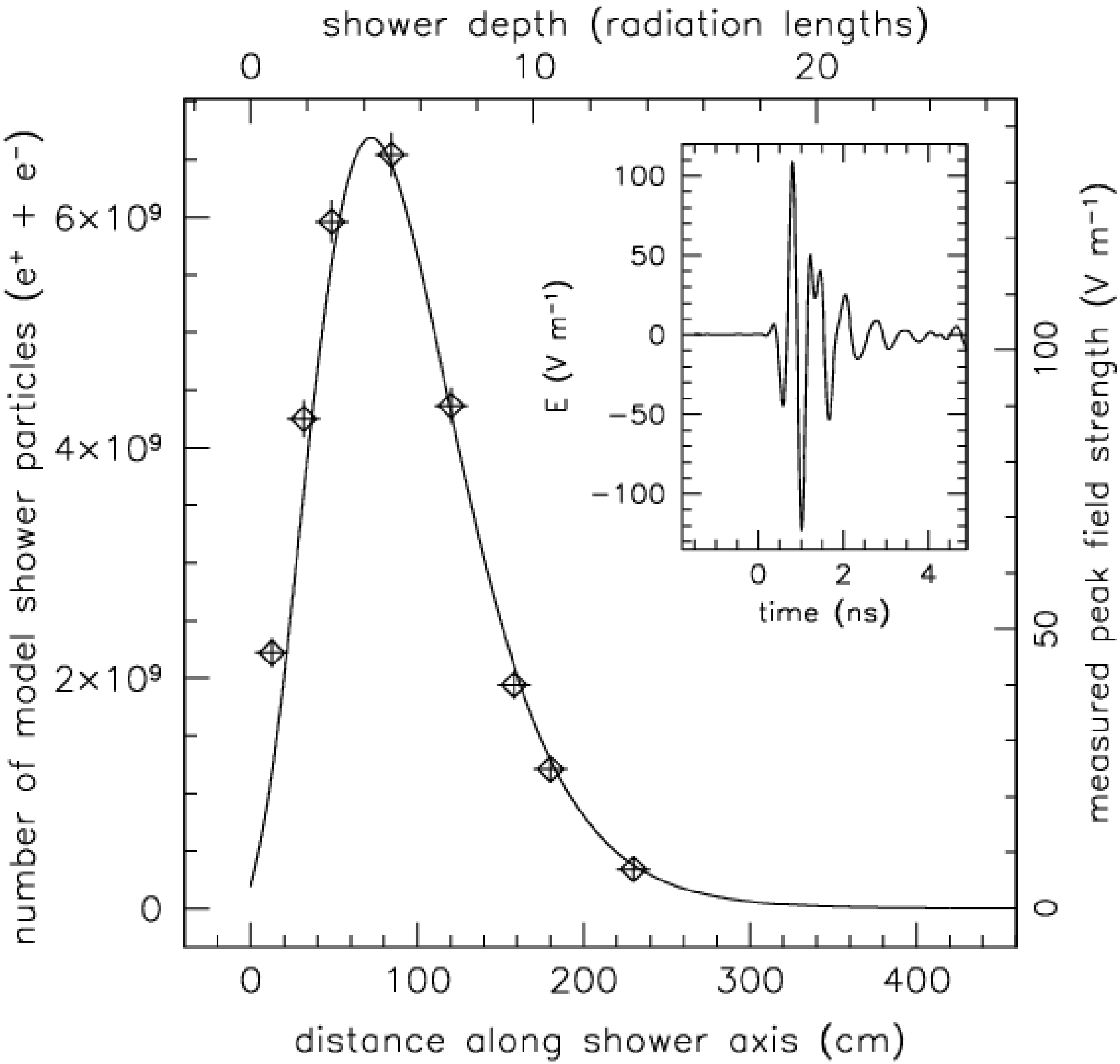
Natural transparent media

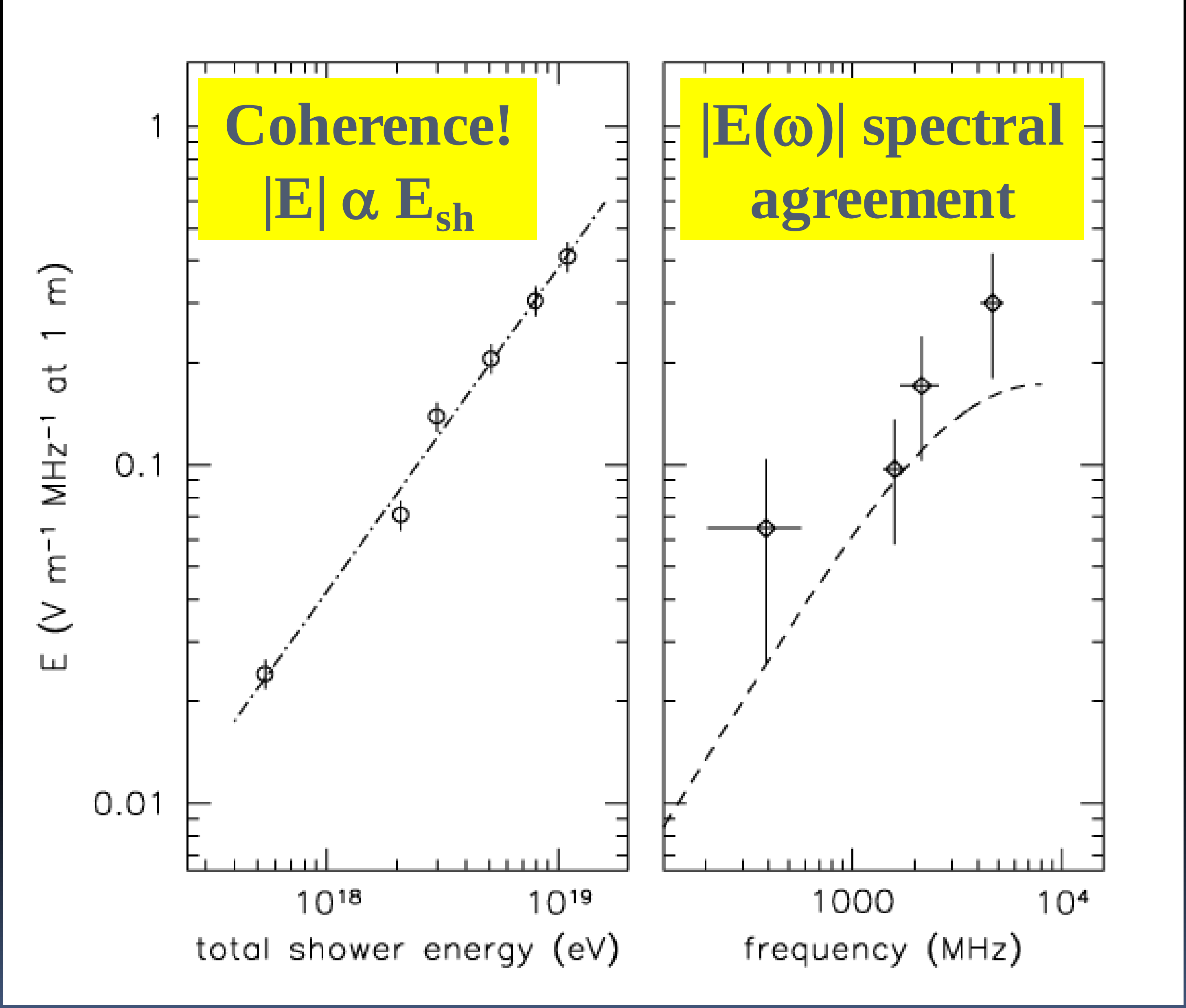
- ICE:
  - Antarctica
    - RICE (array buried)
    - ANITA (balloon)
  - Greenland
    - FORTE (satellite)
- SALT:
  - Domes explored
    - SALSA
- MOON REGOLITH:
  - Radiotelescopes
    - GLUE
  - Radiotelecope array
    - LUNASKA (ska)
- ATMOSPHERE:
  - Antenna array
    - LOFAR

Askary'an effect confirmed: SLAC



P.Gorham, D.Saltzberg et al. PRL (2000)


shower depth (radiation lengths)
0
10
20
number of model shower particles (e⁺ + e⁻)
6×10⁹
4×10⁹
2×10⁹
0
100
50
0
−50
−100
E (V m⁻¹)
0
2
4
time (ns)
100
50
0
measured peak field strength (V m⁻¹)
0
100
200
300
400
distance along shower axis (cm)



Coherence!
|E| α E_sh
|E(ω)| spectral agreement
1
0.1
0.01
E (V m⁻¹ MHz⁻¹ at 1 m)
10¹⁸
10¹⁹
total shower energy (eV)
1000
10⁴
frequency (MHz)

Summary and conclusion:

- Radio Technique has an enormous potential
  - To detect highest energy events
  - To get detail about showers
  - To cover large surfaces
- It is my opinion (and others) that radio could provide the next step in the search for UHE radiation
- There are many projects under consideration
- It is worth investing on them (lot work to do)