ZHAireS and neutrino radio detection

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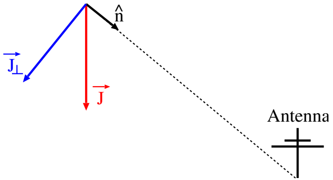
Overview

1. ZHAireS and ZHAireS-Reflex
   - Emission Mechanisms
   - The ZHAireS code
   - Polarization and the Cherenkov ring
   - Some comparisons with data
   - The Two-component approach approximation
   - ZHAireS-Reflex
2. Radio array sensitivity to Earth-Skimming ν_τ
   - End to end simulation
   - Efficiency and Exposure
   - Sensitivity of a radio array

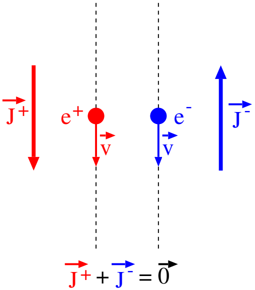
Emission mechanisms

- Two main emission mechanisms:
  - Geomagnetic emission mechanism
  - Askaryan or charge excess emission mechanism
- Moving charged particles radiate
- Movement can be described in terms of a current $\vec{J}(t)$
- From Lienard-Wiechert potentials (disregarding static term):
  - $\vec{E} \propto \frac{\partial \vec{A}}{\partial t} \propto \frac{\partial \vec{J}_\perp}{\partial t}$, where
  - $\vec{J}_\perp = -\hat{n} \times (\hat{n} \times \vec{J})$ and
  - $\hat{n}$ is the observation direction



Askaryan Mechanism

- Dominates emission in dense media
- Electron and positron currents are opposite



$\vec{v}$ approx. paralell to shower axis

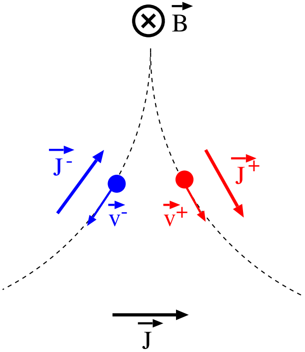
- Emission is due to an excess of electrons in the shower
  - Shower front entrains electrons from medium

    (**Compton**, Møller, Bhabba and positron anihilation)

G.A. Askaryan, Soviet JETP 21 (1965) 658

Geomagnetic mechanism

- Dominates emission in atmospheric showers
- Charged particles deflected by geomagnetic field $\vec{B}$
- Emission from electrons and positrons add up



F.D. Kahn and I. Lerche, Procs. Royal Society A 289 (1966) 206

The ZHAireS code

ZHAireS (ZHS + Aires):

- Simulation of radio emission in air showers and dense media (ice)
- Full shower simulation using Aires
- Radio emission calculation based on ZHS algorithms
- First microscopic simulation with refractive index $n > 1$ and varying $n(h)$
- Can easily simulate emission of neutrino induced showers (special primary)

AstropaPhys, **35**, 325, 2012 and AstropaPhys, **35**, 287, 2012

ZHS algorithms:

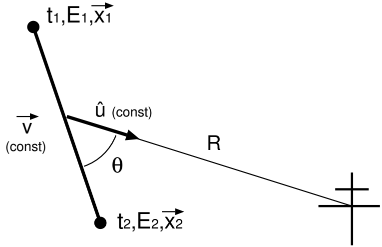
- First principles (Maxwell) - No emission model presupposed.
- Geomagnetic, Charge Excess (Askaryan), etc... all included
- Frequency- and Time-domain calculations of vector potential $\vec{A}$ and electric field $\vec{E}$

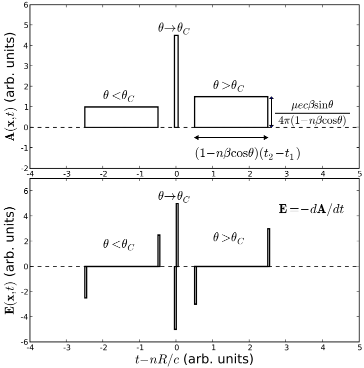
Zas, Halzen, Stanev, Phys.Rev.D V**45**, 362 (1992) and Phys.Rev.D81:123009,2010

Extended ZHS algorithms: Time and Frequency domains

- Time domain
$$\vec{A}(t,\hat{u}) = \frac{\mu e}{4\pi R c}\vec{\beta}_\perp \frac{\Theta(t-t_1^{det})-\Theta(t-t_2^{det})}{1-n\vec{\beta}\cdot\hat{u}}$$

- Frequency domain
$$\vec{E}(\omega,\hat{u}) = -\frac{\mu e}{2\pi c}\vec{\beta}_\perp \frac{e^{i\omega(t-t_1^{det})}-e^{i\omega(t-t_2^{det})}}{1-n\vec{\beta}\cdot\hat{u}}$$





Santiago group, Phys.Rev.D**81**,123009 (2010)

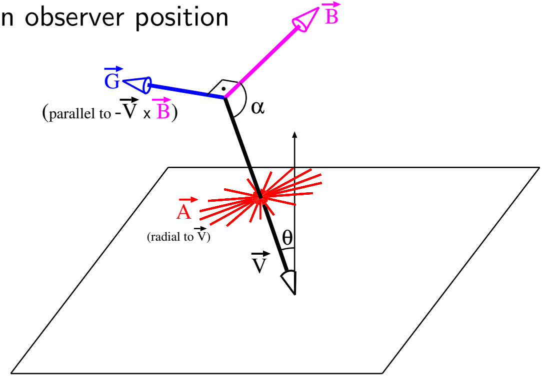
Polarization

Geomagnetic mechanism polarization ($\vec{G}$)

- Aproximatelly paralell to $-\vec{V} \times \vec{B}$
- Independant of observer position

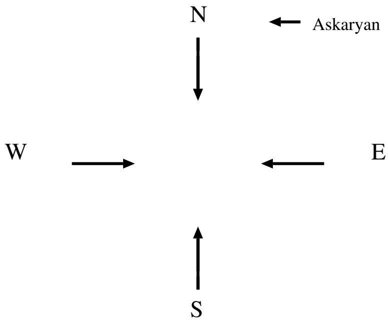
Askaryan mechanism polarization ($\vec{A}$)

- Aproximatelly radial w.r.t. shower axis $\vec{V}$
- Depends on observer position



Superposition of emission mechanisms: Asymmetries

Vertical shower with horizontal $\vec{B}$



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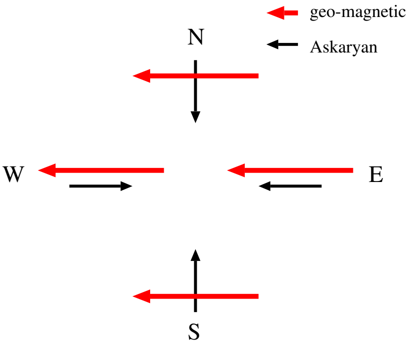
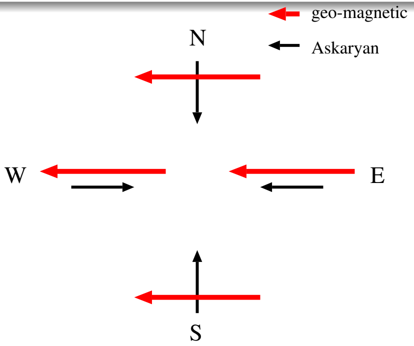


Superposition of emission mechanisms: Asymmetries

Vertical shower with horizontal $\vec{B}$

North of core

EW component: pure geomagnetic
NS component: pure Askaryan



South of core

EW component: pure geomagnetic
NS component: pure Askaryan

Superposition of emission mechanisms: Asymmetries

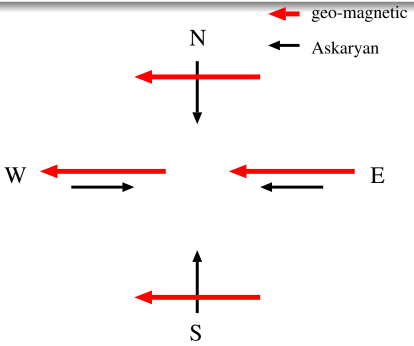
Vertical shower with horizontal $\vec{B}$

North of core

EW component: pure geomagnetic
NS component: pure Askaryan

West of core

Askaryan and geomagnetic have **opposite** directions: They **subtract**



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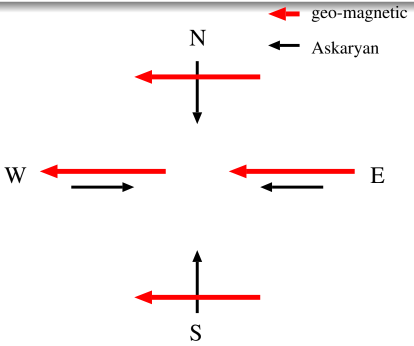

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Askaryan and geomagnetic are parallel: They **add up**

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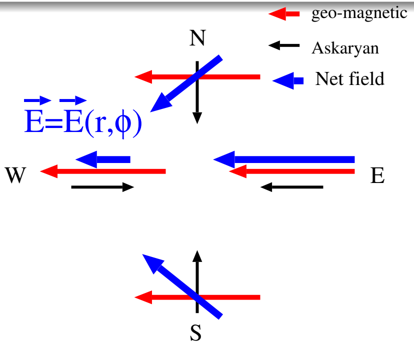

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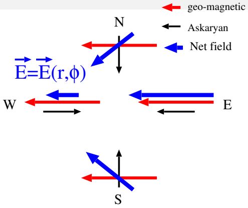
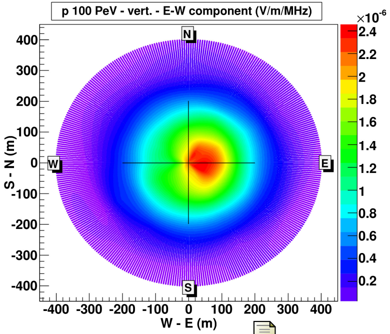
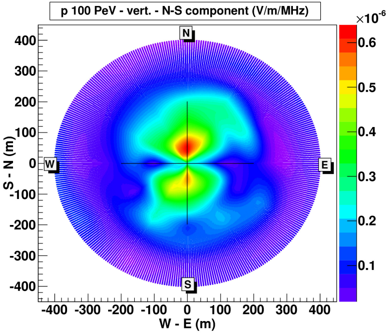


EW component



NS component

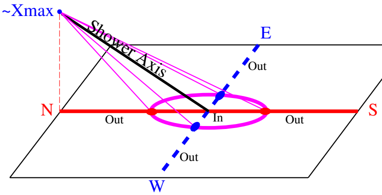


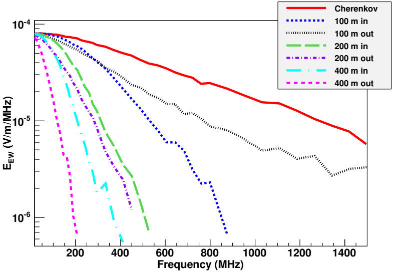
Astropar. Phys., **35**, (2012) 325

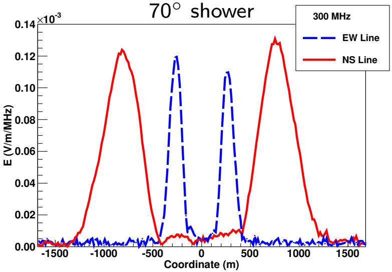
Cherenkov Ring

Observers that see X_{max} at θ_C

- Define a ring-like region on the ground
- Maximum field amplitude
- Sizeable intensity well into the GHz range
- Ring is elliptical for non-vertical showers

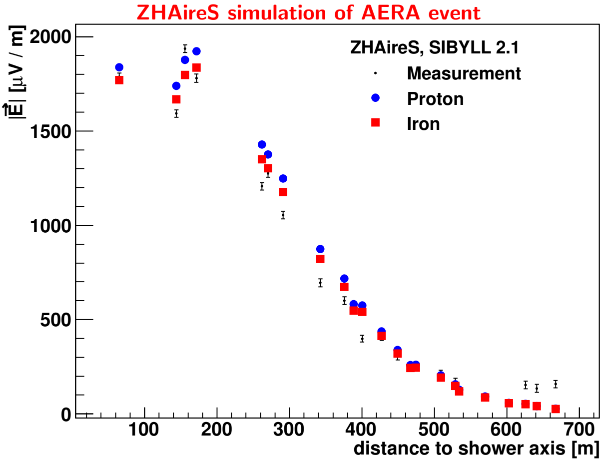






J. Alvarez-Muñiz, W. Carvalho Jr., A. Romero-Wolf, M. Tueros, E. Zas, Phys. Rev. **D 86** (2012) 123007

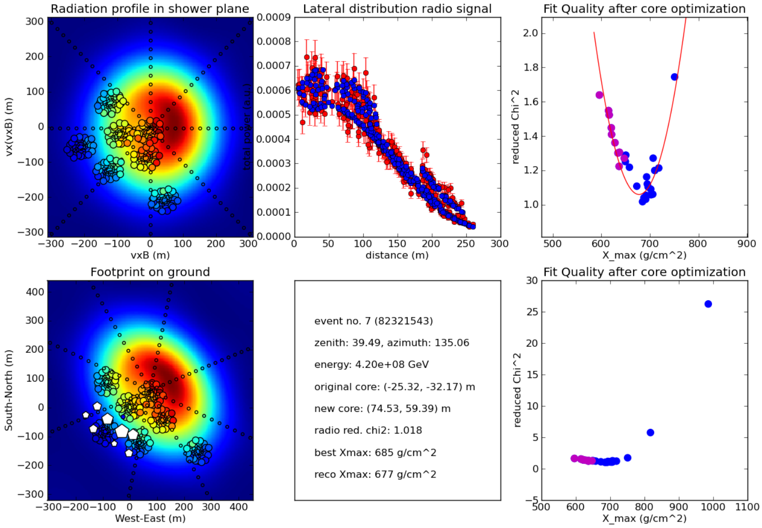
ZHAireS simulations in good agreement with data



Pierre Auger Collaboration, ICRC2013, id #899

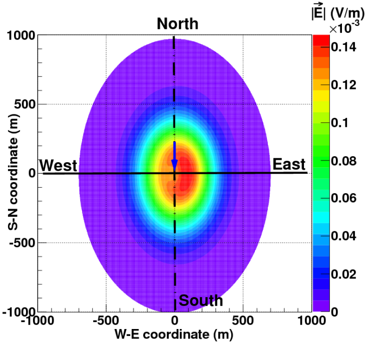
Very good agreement of the RLDF shape

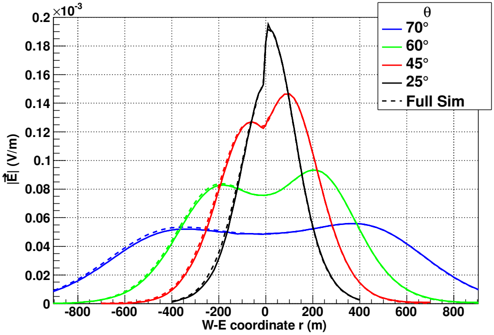
LOFAR X_{max} reconstruction using ZHAireS simulations ($\sigma_{X_{max}} \sim 20 g/cm^2$)



Two-component approach approximation

- Significantly reduces computing time
- Based on superposition of Askaryan and geomagnetic components
- Field at any position extrapolated from few antenna simulations
- Very good agreement with full simulation for most geometries

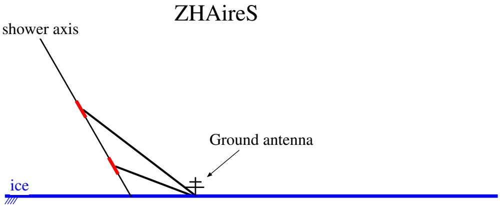




Astropar. Phys., **59** (2014) 29

ZHAireS-Reflex

- Special ZHAireS code
- Reflection on ground (ice) and propagation to a high altitude detector
- Includes the Fresnel reflection coefficients



Astropar. Phys **66 (2015) 31-38**

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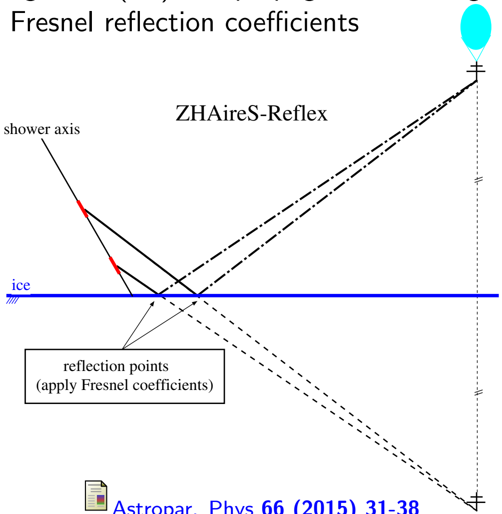

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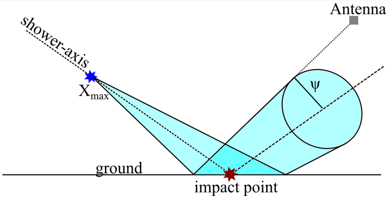
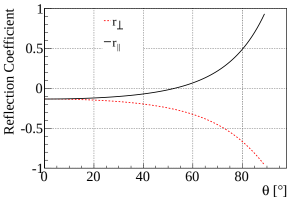
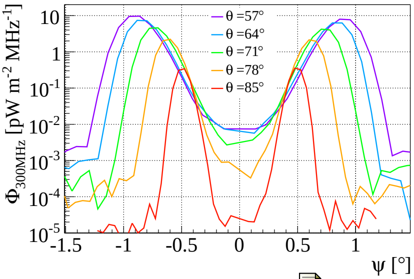
Fresnel coefficients

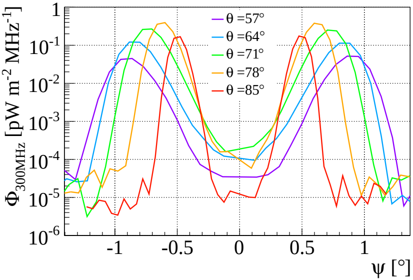




No Fresnel coefficients



With Fresnel coefficients



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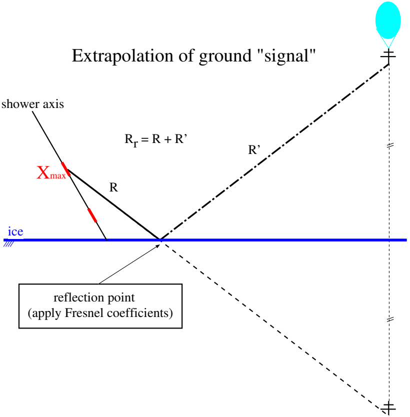
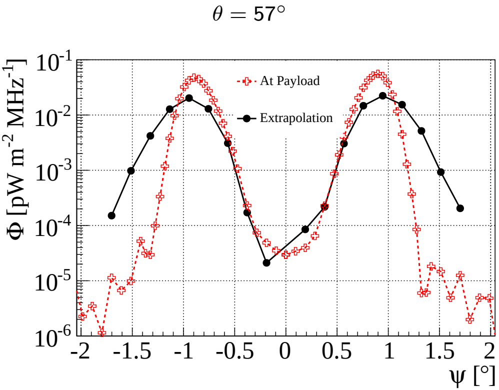
Full reflection simulation vs. ground signal extrapolation





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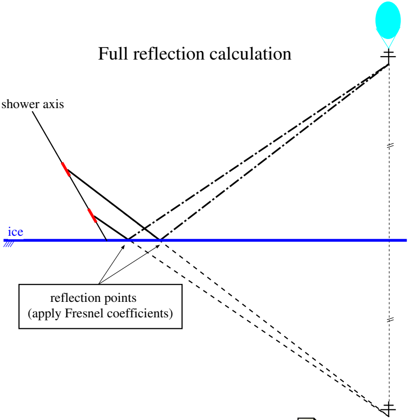

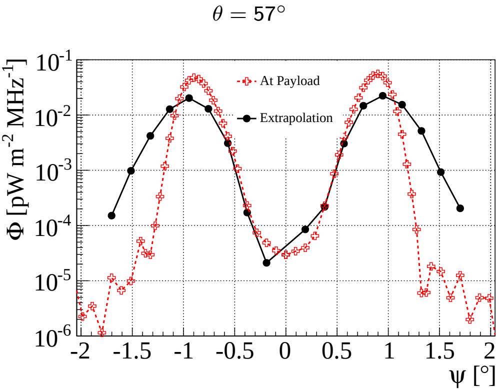

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Summary

- We now have a good undertanding of the radio emission of EAS
- ZHAireS can describe the details of this emission
- Good agreement with data
- A simple two-componnet approach can be used to drastically reduce computing time
- ZHAireS-Reflex performs full reflection simulations
- Fresnel coefficients of utmost importance
- Full reflection simulations differs considerably from ground signal extrapolation

Radio array sensitivity to Earth-Skimming ν_τ

Jaime Alvarez-Muñiz[1] Pablo Pieroni[2]

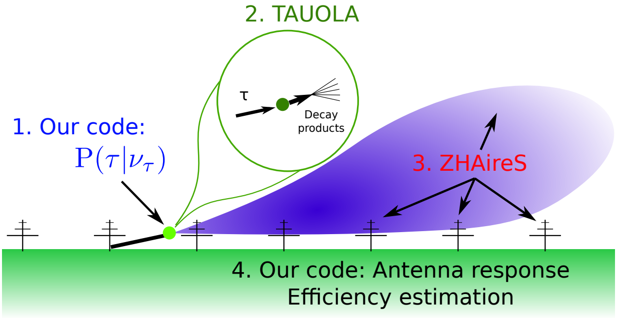
[1]Departamento de Física de Partículas & Instituto Galego de Física de Altas Enerxías
Universidad de Santiago de Compostela, España.

[2]Departamento de Física - Facultad de Ciencias Exactas y Naturales
Universidad de Buenos Aires, Argentina.

February 9$^{\text{th}}$ 2015

End to end simulation

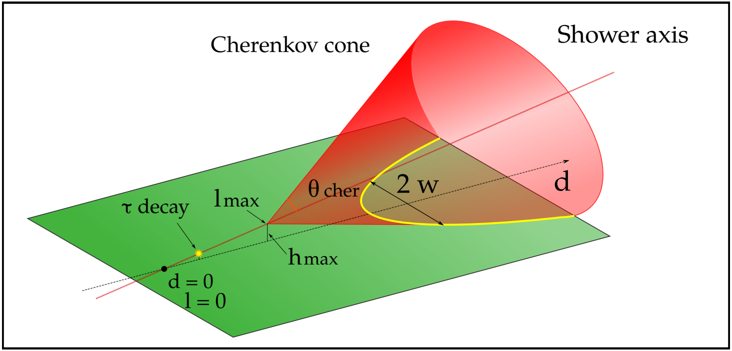
Simulation stages



1. $\mathrm{P}(\tau, \nu_\tau)$: Probability to obtain a τ with (E_τ, θ) given a ν_τ with (E_ν, θ) using our code
2. τ decay products obtained with TAUOLA
3. Shower evolution and antenna signal calculation with ZHAireS
4. Antenna response and efficiency calculation using our code

Radio footprint

Cherenkov emision projected on the ground

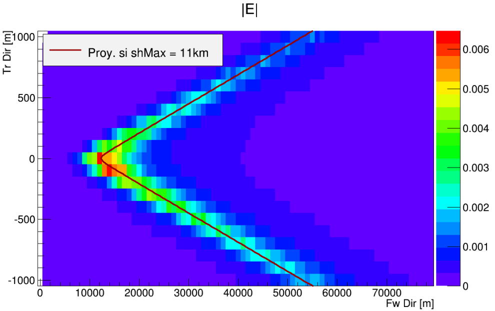


Width w of hyperbola:

$$w^2 = \left[\tan^2\theta_{cher} - \tan^2\left(\theta - \frac{\pi}{2}\right)\right]\left(\frac{d}{\sin\theta} - l_{max}\right)^2 - \tan\left(\theta - \frac{\pi}{2}\right)\frac{h_{max}}{\sin\theta}\left(\frac{d}{\sin\theta} - l_{max}\right) - \frac{h^2_{max}}{\sin^2\theta}$$

Radio footprint

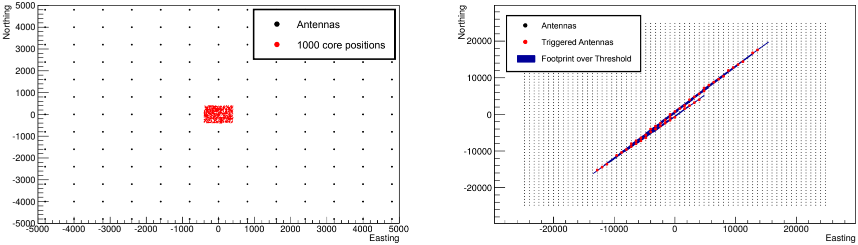
Energy of the tau that goes into shower ~ 1 EeV



1. Very elongated and narrow footprints (hyperbola)
2. In agreement with prediction from simple model of Cherenkov cone emission

Efficiency calculation

Shower energy: 1 EeV



- Example: Squared grid array. 900 m separation between antennas.
- Big enough to contain the whole radio footprint (hyperbola).
- 1000 random core positions in each ($E_{shower}, \theta, \tau_{\mathrm{decay\ Height}}$) bin.
- Antenna response $30 - 80$ MHz/$150 - 900$ MHz.
- Trigger if *n* antennas above threshold (selected by user)
- Neutrino identification efficiency (conservatively) assumed to be 90%
  - Based on the apparent velocity of the signal and the width *w* of the footprint.
  - Identification criteria not yet optimized

Exposure calculation

Formula

$$\mathcal{E}(E_\nu) = 2\pi\, TA \int_0^\infty \int_{\theta^{cut}}^{\theta^{max}} \int_0^{E_\nu} \int_0^{E_\tau} \epsilon(X_d, \theta, E_{sh}) \frac{e^{-\frac{l(X_d)}{\lambda(E_\tau)}}}{\lambda(E_\tau)} \frac{dl(X_d)}{dX_d} P(E_{sh}|E_\tau)$$
$$P(E_\tau|E_\nu, \theta) \sin\theta \cos\theta\, dE_{sh}\, dE_\tau\, d\theta\, dX_d$$

Ingredients

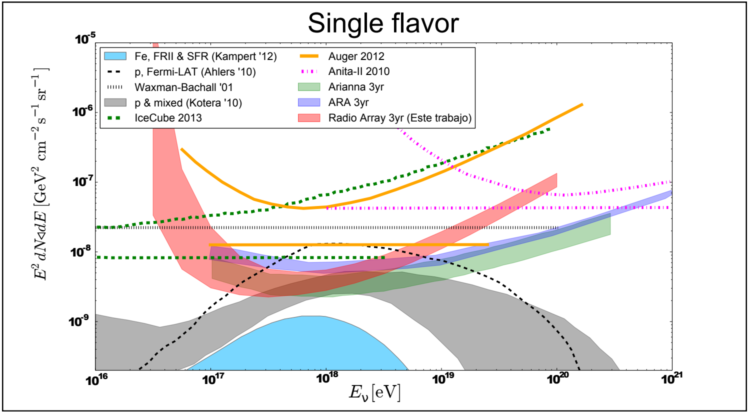
- Time and area
- Trigger and ν identification efficiency
- Probability of τ decay at vertical depth X_d in atmosphere.
- Probability of τ of energy E_τ producing shower of energy E_{sh}
- Interaction of ν_τ inside Earth
- Solid angle

Sensitivity of a radio array (3 yr)

Differential limit calculation

Assume ν flux: $\Phi_\nu = k\ E_\nu^{-2} \Rightarrow Sensitivity = \frac{2.4}{E_\nu^{-2}\ \mathcal{E}(E_\nu)\Delta E_\nu}$ with ΔE_ν = half a decade in E_ν

Radio array: 90,000 antennas, 900 $\times$ 900 m grid - Trigger threshold 50-350 $\mu\mathrm{V/m}$



Questions?

Other applications of Radio...

Askaryan Mechanism

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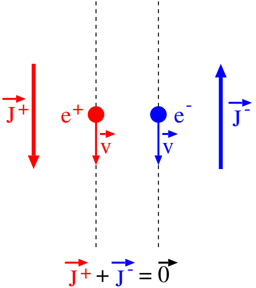
- Electron and positron currents are opposite



$\vec{v}$ approx. paralell to shower axis

- Emission is due to an excess of electrons in the shower
  - Shower front entrains electrons from medium
    (**Compton**, Møller, Bhabba and positron anihilation)

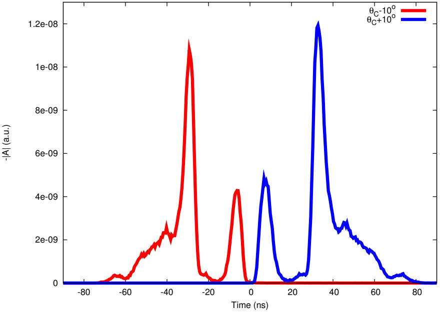
G.A. Askaryan, Soviet JETP 21 (1965) 658

$\vec{A}_{Ask}$ reflects the charge excess

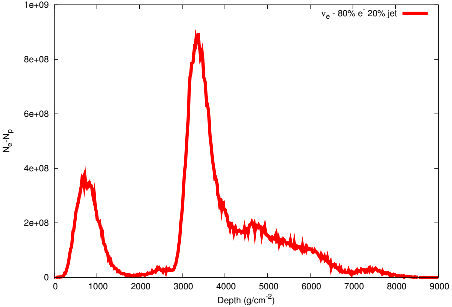
- ZHAireS: Ice ν_e cascade with E_0 =10 EeV
- CC with $0.8E_0$ going into an e^- (LPM!!!)

NIMA **662**, S187-S190, (2010) - ARENA2010

$|\vec{A}_{Ask}|$



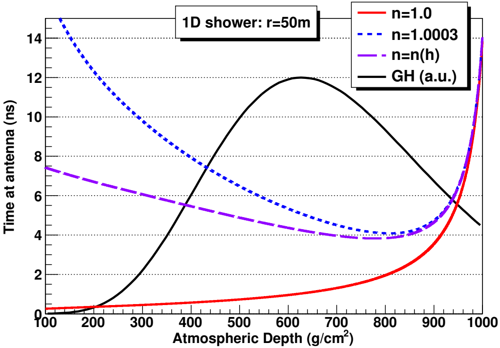
Charge excess vs. atmospheric depth



Cherenkov-like effects

Relativistic effects play crucial role in emission

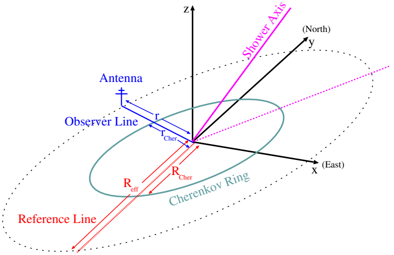
- Stem from atmospheric refractive index $n > 1$ (n=1.000325 @ sea level)
- Shower front travels faster than emission
- Time reversal / multiple parts of EAS seen simultaneously
- Large "time compression" around part seen at $\theta_C = cos^{-1}(1/n)$

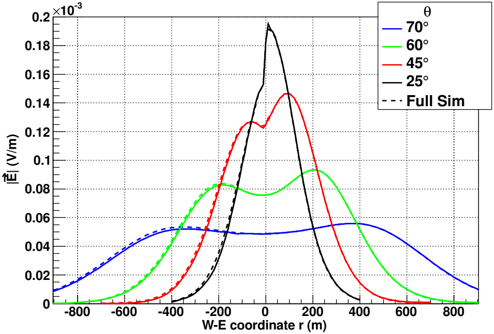


Astropar. Phys., **35**, (2012) 325

Two-component approach approximation

- Significantly reduces computing time
- Superposition of Askaryan and geomagnetic components assuming their theoretical polarizations and elliptical symmetry
- Field at any position can be extrapolated from of a single line of antenna simulations
- Very good agreement with full simulation for most geometries





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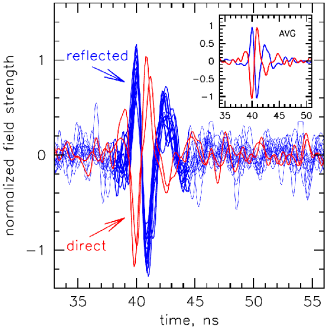
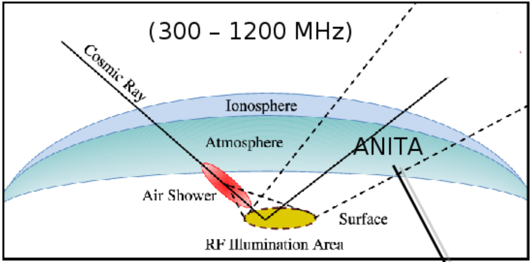
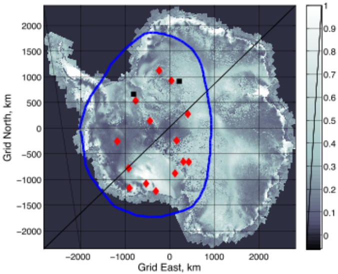
ANITA UHECR detection

- Designed for detection of ν showers in antarctic ice
- detected 16 UHECR: 14 of them reflected on ice
- Compatible with Geomagnetic mechanism
- GHz emission due to time compression effects







USC: Long tradition in the radio technique

ZHS: First simulations of radio emission (Dense media-Askaryan)

- 1990: **Z**as (USC), **H**alzen (Univ. Winscosin) and **S**tanev (Univ. Delaware)
- Algorithm based on first principles
- Dense media, EM shower, Frequency domain
- Several later studies/developmnets

ZHAireS: ZHS + AIRES

- 2009: ZHS algorithm extended to the time domain and Fresnel approximation
- Full shower simulation (AIRES)
- Air Showers and Dense Media (TIERRAS)
- First microscopic simulation with refractive index $n > 1$ and varying $n(h)$
- 2013: Only simulation capable of simulating reflected events (ANITA, SWORD)