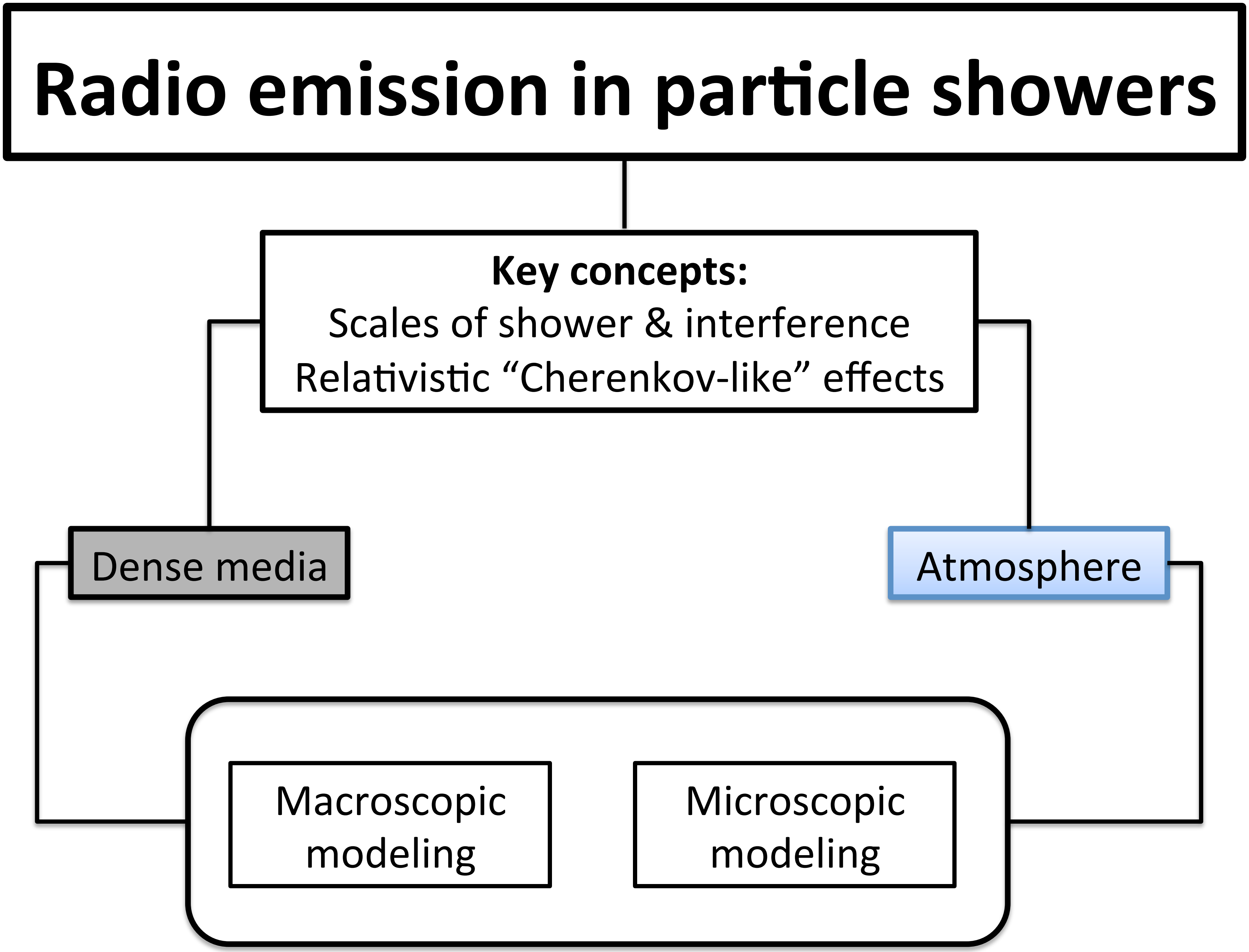
Modeling radio emission from particle showers in dense media & air: a pedagogical overview

Jaime Alvarez-Muñiz

Univ. Santiago de Compostela, Spain

In collaboration over the last ~ 20 years with:
J. Bray, R. Ekers. C.W. James, W. R. Carvalho Jr. , D. García-Fernández, F.Halzen, R. McFadden, A. Romero-Wolf , R.J. Protheroe, H. Schoorlemmer, D. Seckel, T. Stanev, M. Tueros, R.A. Vázquez, E. Zas

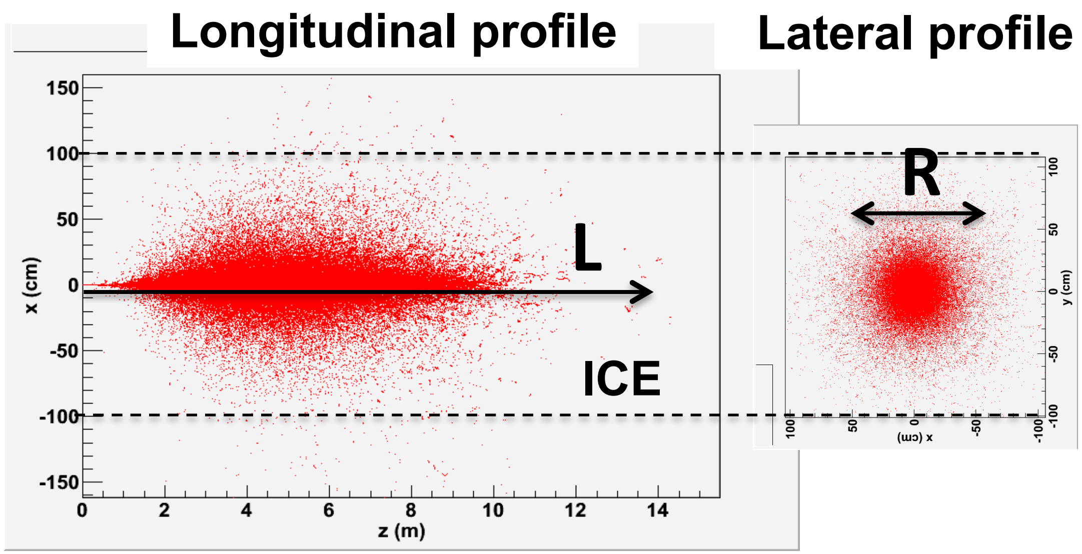
ARENA 2014, 7-12 June 2014, Annapolis (USA)

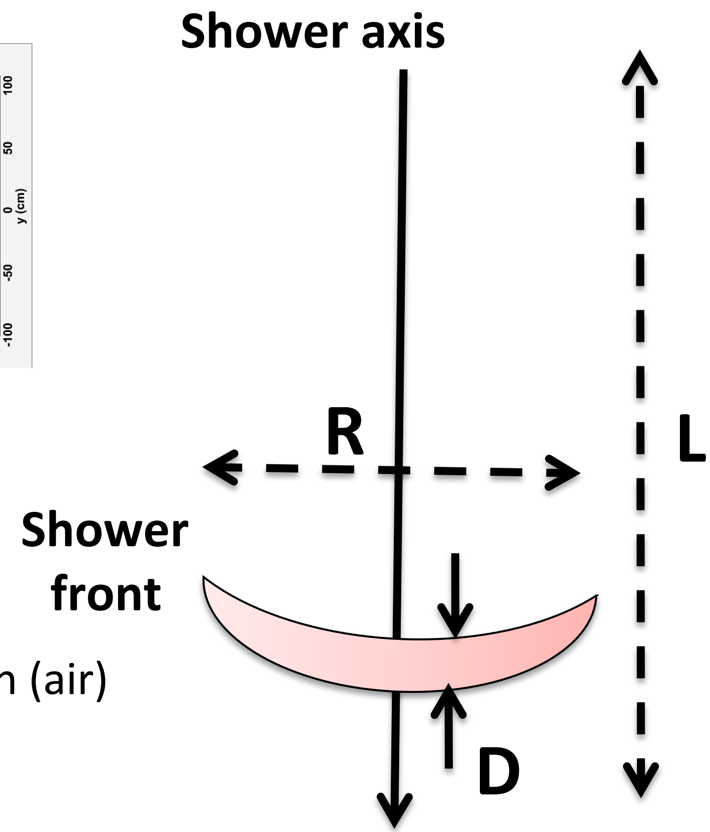

Radio emission in particle showers
Key concepts:
Scales of shower & interference
Relativistic "Cherenkov-like" effects
Dense media
Atmosphere
Macroscopic modeling
Microscopic modeling

A few key concepts

The (complex) source of radiation

- **Particle shower** developing in dense media or in air.





- **Net charge** arises mainly due to:
  - Askaryan effect (dense media)
  - Askaryan effect + geomagnetic charge separation (air)
- Shower characterized by **three scales**:
  - Scale of **longitudinal** development (L)
  - Scale of **lateral** spread (R)
  - **Thickness** of **shower front** (D)

Interference & coherence

Fields radiated by shower particles **interfere** with each other:

- If observation wavelength λ **>> shower dimensions**:
  - all fields add with approx. same phases $\Longrightarrow$ **coherent emission**
  - total field proportional to number charged particles N ~ E_{shower}
  - power ~ N^2 ~ E^2_{shower}
- If λ **< shower dimensions**:
  - fields contribute with varying phases $\Longrightarrow$ **destructive interference** sets in.
  - cut-off in the frequency (ω) spectrum.
  - shower scale (L, R or D) responsible for cut-off depends on ω and observer position.

- **Finite space-time dimensions of source** $\Longrightarrow$

  for $\omega \longrightarrow 0 \Longrightarrow$ radiative field $\longrightarrow 0 \Longrightarrow$ time integral of pulse should vanishes $\Longrightarrow$ equally large positive & negative amplitudes $\Longrightarrow$ **bi-polar pulses**

1D "line" model of shower development

Assumptions:

a. 1D line of current (net constant charge Q) spreading over length L.
b. Lateral R=0 & Width D=0
c. Charge travels at v = c > c/n

Far-field observer at Cherenkov angle θ_C

$$t_{1\rightarrow 2} = L/v = t_{1\rightarrow 3} = L\cos\theta_C / (c/n)$$

Wavefronts **in phase**

$$\cos\theta_C = 1/(n\beta)$$

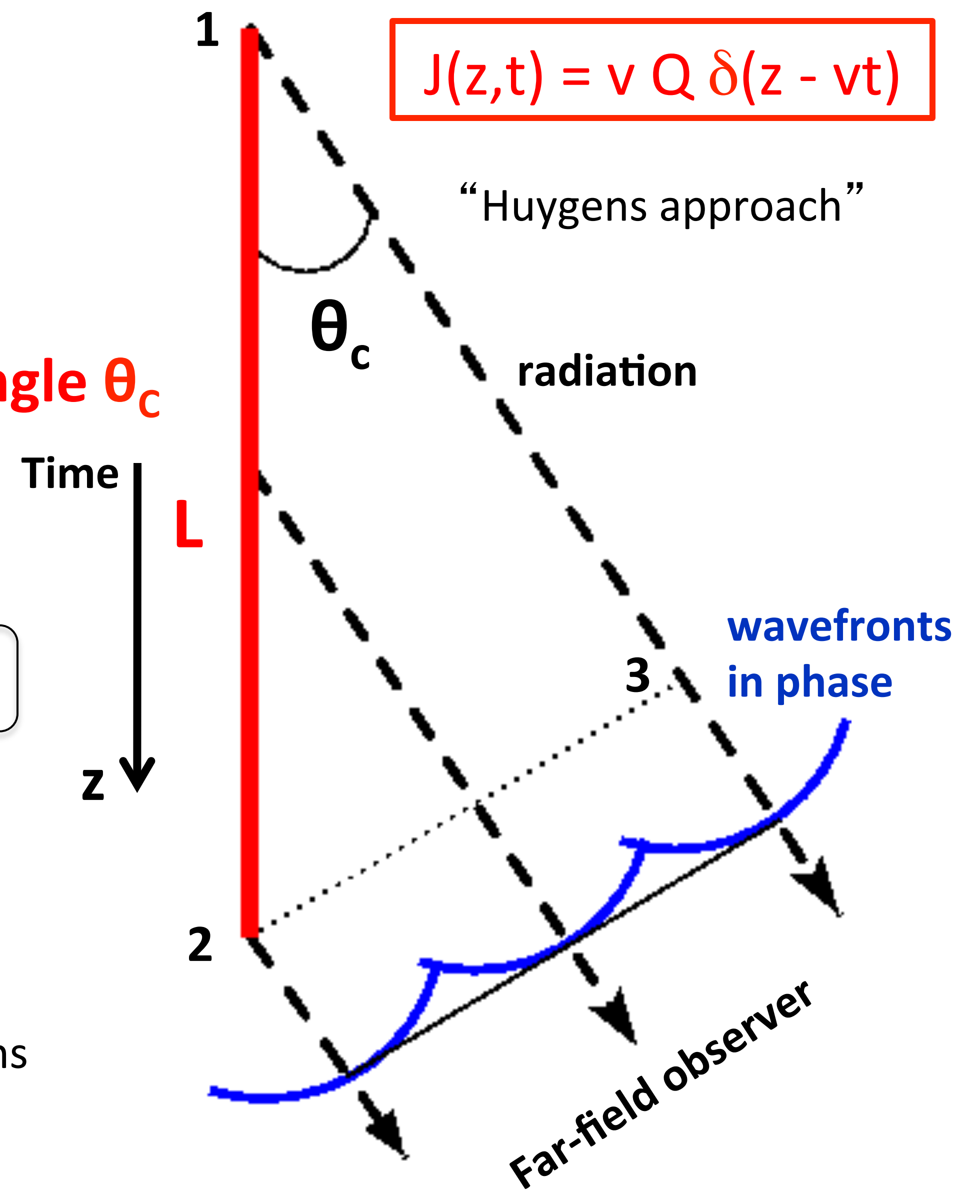
Time-domain:

- Observer sees **whole shower "at once"** (sensitivity to longitudinal scale L lost…)

Frequency domain:

- **Constructive interference** at ALL wavelengths
- Spectrum increases linearly with frequency: **NO frequency cut-off**

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



1D "line" model of shower development

Far-field observer at $\theta \neq \theta_c$

Wavefronts **NOT in phase**
(due to **longitudinal shower spread L)**

Time-domain

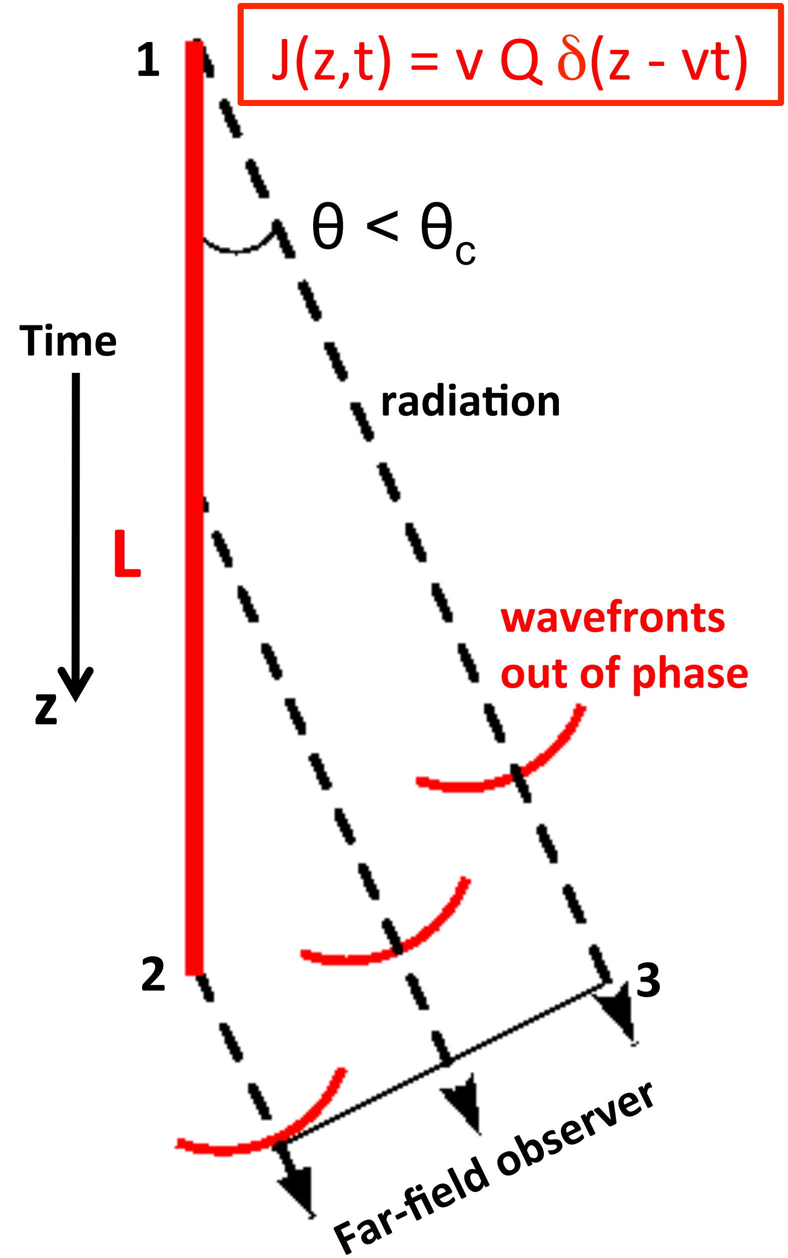
- Observer sees radiation in a **finite interval of time** depending on angle (sensitivity to scale L):

$$\Delta t_L\,(L,\theta) \approx L\,(1 - n\cos\theta)\,/\,c$$

Frequency domain

- Spectrum increases linearly with ω up to **Frequency cut-off**

$$\omega_{cut}(L,\theta) \approx 1/\Delta t_L$$



Relativistic effects

n > 1 & particles travel at v > c =>
"Cherenkov-like" relativistic phenomena

Source position/time (z,t) mapped to observer time (t_{obs}) via θ –dependent relation:

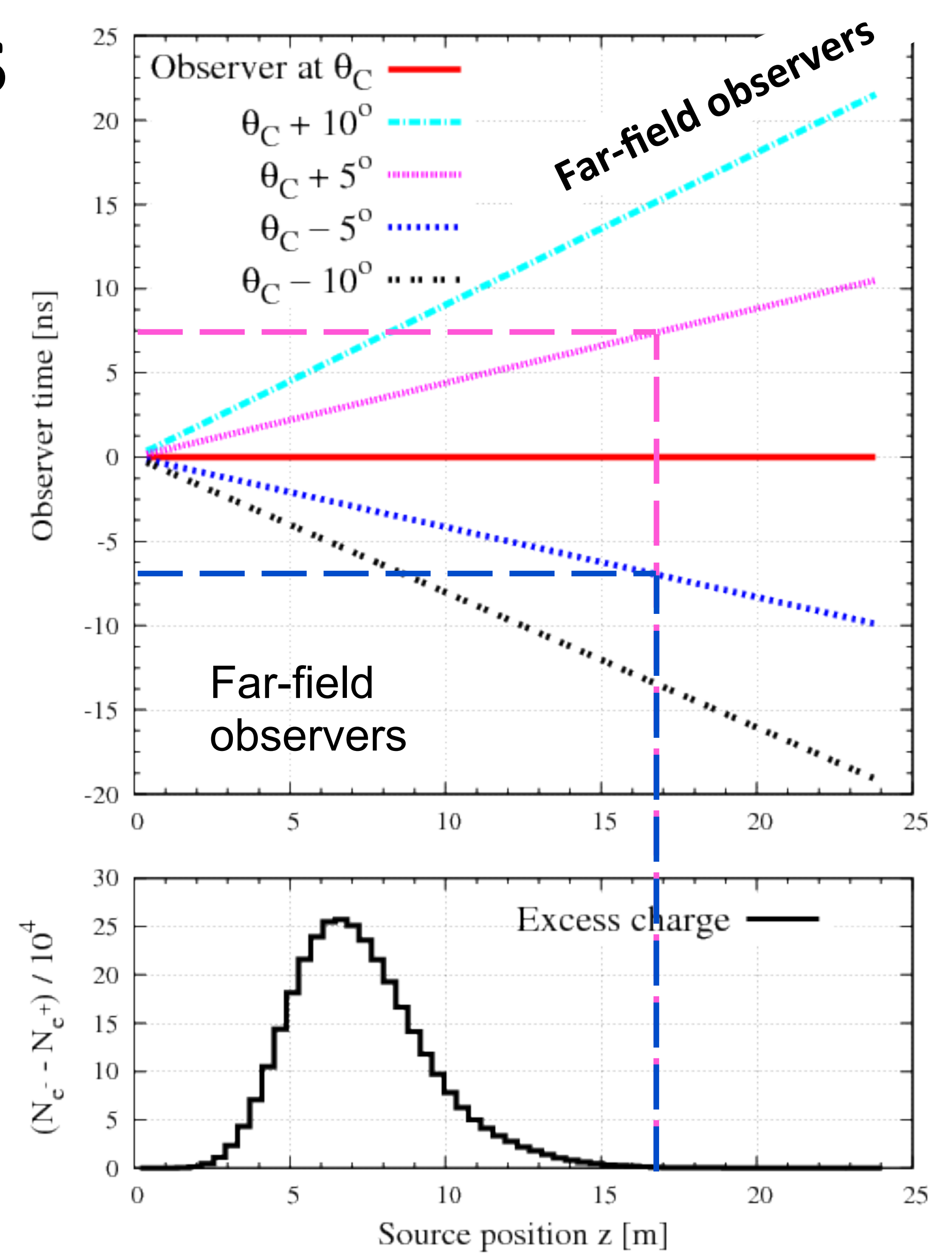
$$t_{obs} = z\,(1 - n\cos\theta)/c + t_0$$

θ = θ_c => observer sees shower at $t = t_0$

As observer moves from θ_c shower appears to last longer in time.

θ > θ_c => observer sees first the start of shower and then the end (causality)

θ < θ_c => observer sees first end of the shower and later the start (non-causality)



2D "box" model of shower development

Assumptions:

1. 2D current: extending longitudinally over L & laterally over R.
2. Width D=0.
3. Uniform excess charge Q. v > c/n

Far-field observer at Cherenkov θ_c

Wavefronts **NOT in phase** (due to **lateral spread R of shower**).

Time-domain:

- Observer sees radiation in **finite interval of time**:

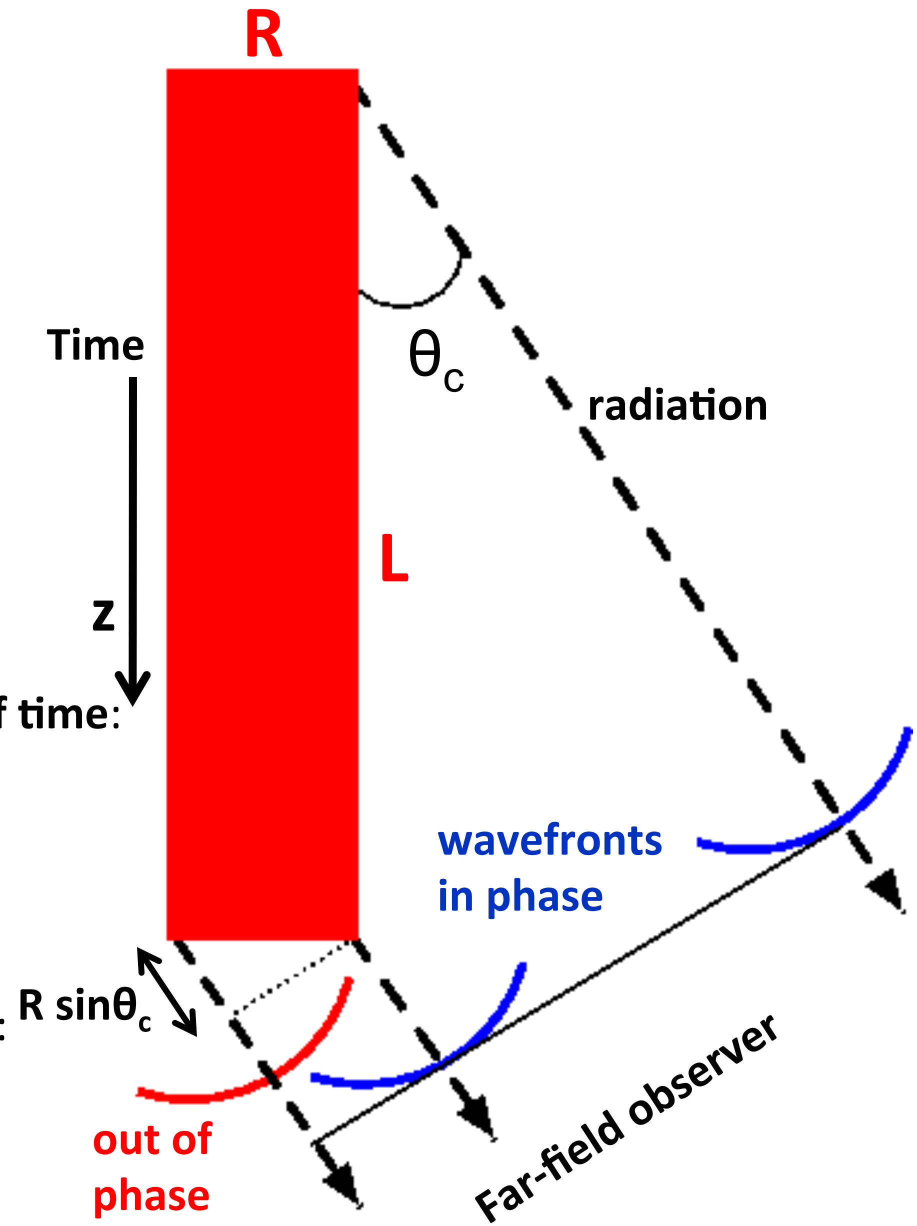
$$\Delta t_R \approx R \sin\theta_c / (c/n)$$

Frequency domain:

- Spectrum increases linearly with frequency:

Frequency cut-off

$$\omega_{cut}(R) \approx 1/\Delta t_R$$



2D "box" model of shower development

Far-field observer at $\theta \neq \theta_c$

Wavefronts **NOT in phase**
(due to **longitudinal** L & **lateral** spread R of shower)

Time-domain:

- Observer sees radiation in **finite interval of time**:

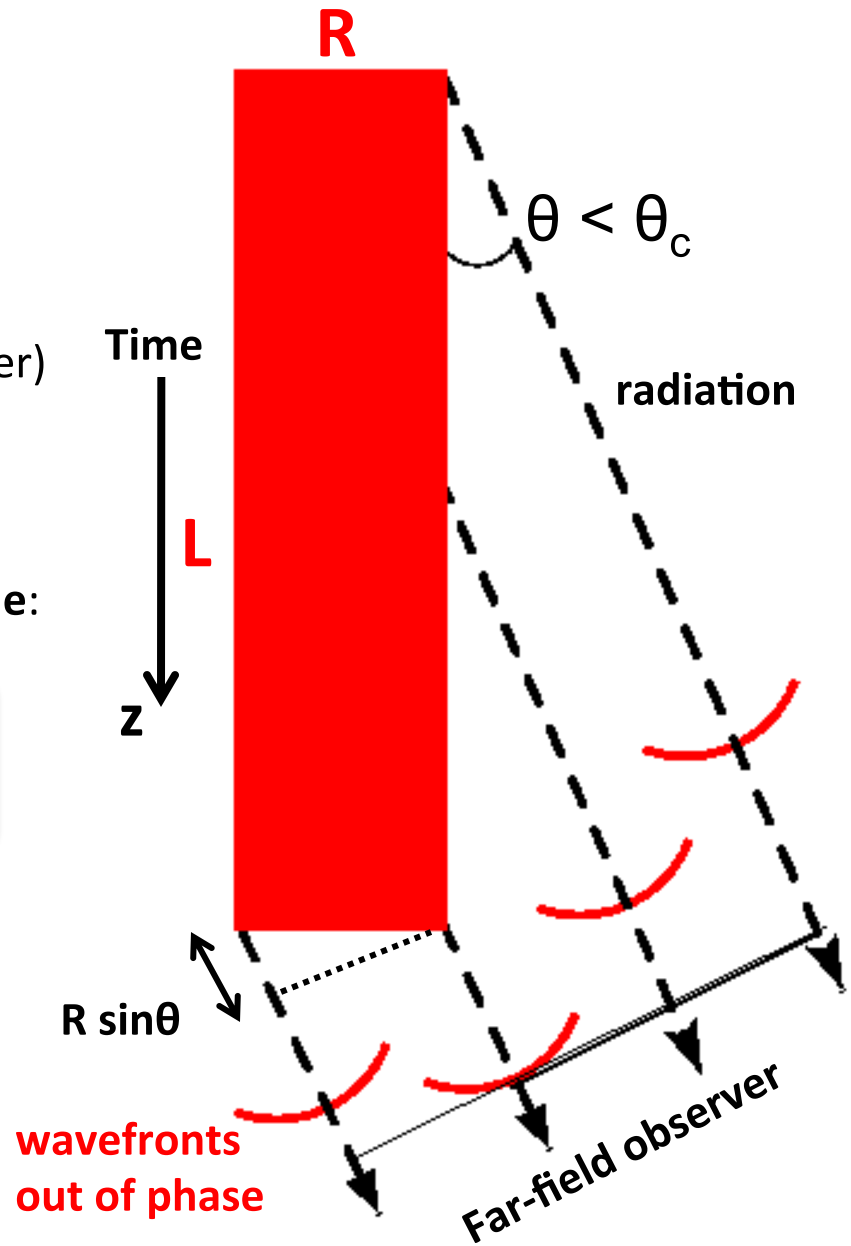
$$\Delta t \sim \max\,[\Delta t_R(R,\theta)\,,\,\Delta t_L(L,\theta)] = \max\,[nR\sin\theta/c,\ L\,(1 - n\cos\theta)/c]$$

Frequency domain:

- Spectrum increases linearly with ω up to

Frequency cut-off

$$\omega_{cut} \approx 1/\Delta t$$



2D "box" model of shower development with shower front thickness

Far-field observer at $\theta \neq \theta_c$

Wavefronts **NOT in phase**
(due to **longitudinal** L & **lateral** spread R of shower & width of shower front D)

Time-domain:

- Observer sees radiation in **finite interval of time**:

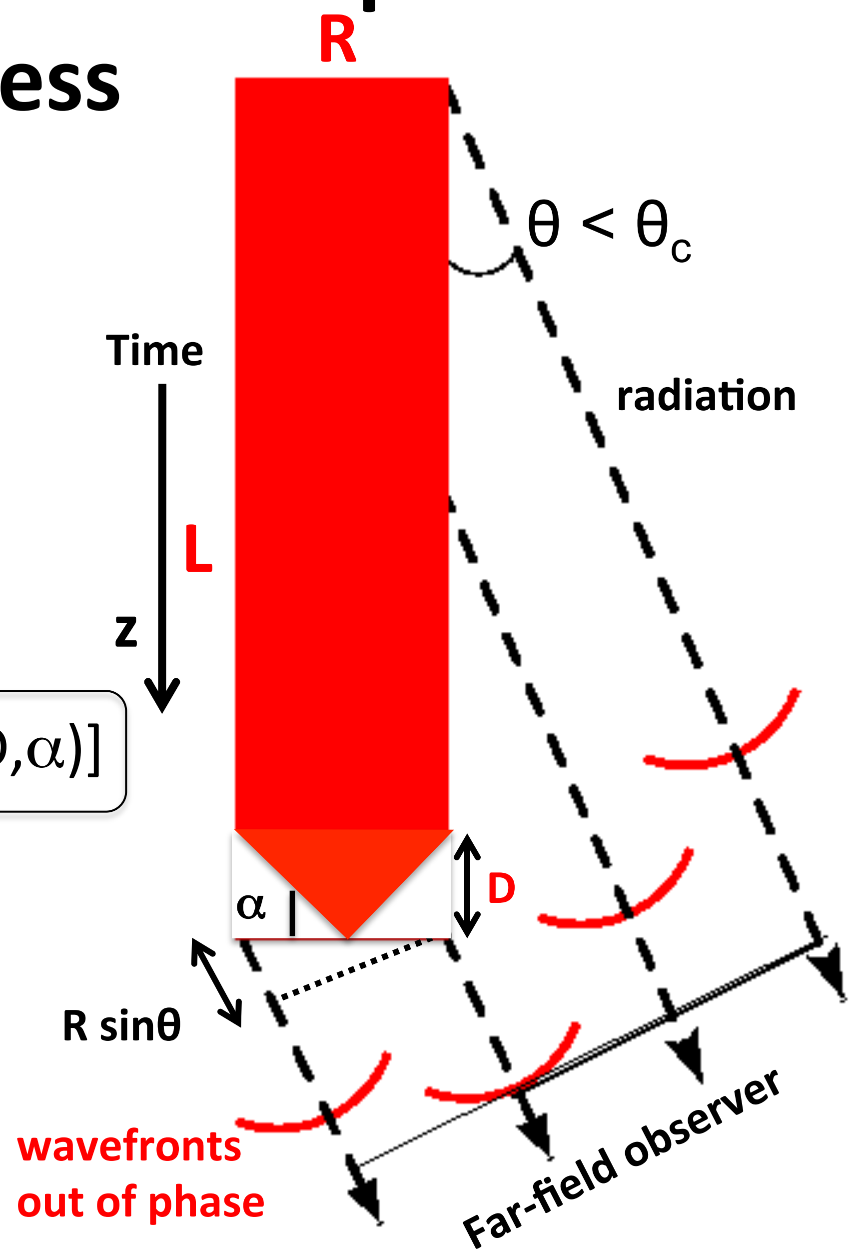
$$\Delta t \sim \max\left[\Delta t_R(R,\theta)\,,\ \Delta t_L(L,\theta)\,,\ \Delta t_D(\theta,R,D,\alpha)\right]$$

$\Delta t_D \approx nR[(1+D^2/R^2)^{1/2}\sin(\theta-\alpha)-\sin\theta]$
(assuming a conical shower front model)

Frequency domain:

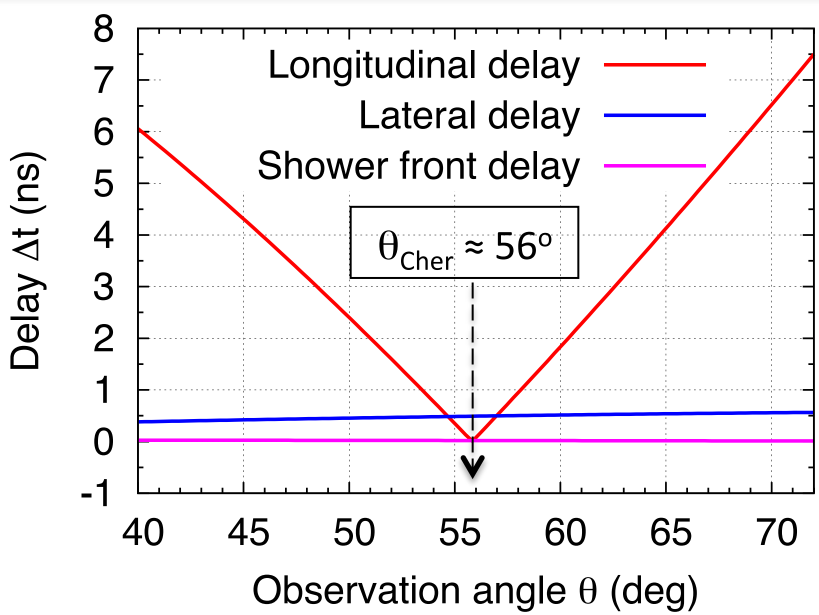
- Spectrum increases linearly with ω up to **Frequency cut-off**

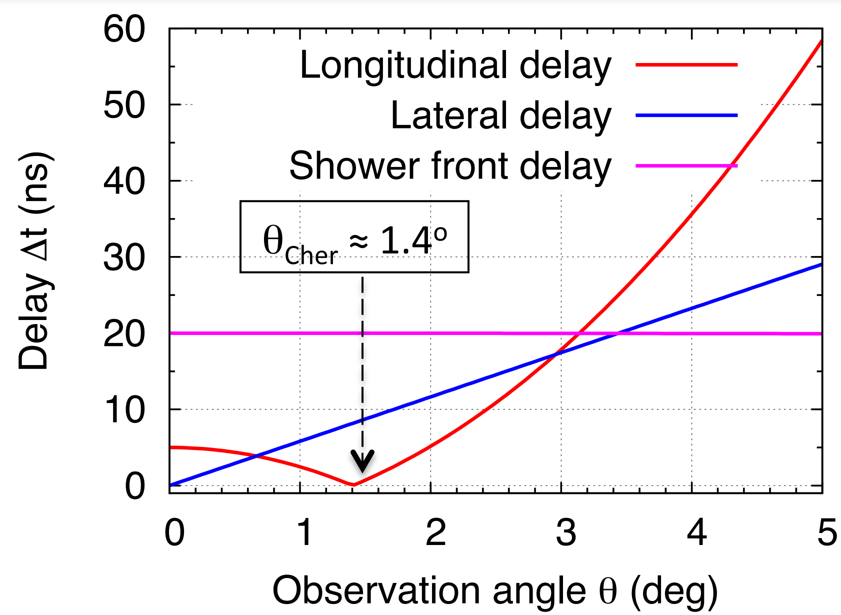
$$\omega_{cut} \approx 1/\Delta t$$



Ice		Air
Longitudinal delay	**Lateral delay**	**Shower front thickness delay**
$\Delta t_L \approx L\,(1 - n\cos\theta)/c$	$\Delta t_R \approx nR\sin\theta/c$	Δt_D

Ice	Air
$L \approx 5$ m, $R \approx 0.1$ m, $n = 1.78$, $\theta_{Cher} \approx 56^o$	$L \approx 5$ km, $R \approx 100$ m, $n = 1.0003$, $\theta_{Cher} \approx 1^o$
$\theta \approx \theta_{Cher} \Longrightarrow \Delta t_R > \Delta t_D > \Delta t_L \sim 0$ Lateral delay $\Longrightarrow$ cutoff @ ~ 1 GHz	$\theta \approx \theta_{Cher} \Longrightarrow \Delta t_D >> \Delta t_R > \Delta t_L \sim 0$ Shower front delay $\Longrightarrow$ cutoff @ 10's MHz
θ away from θ_{Cher} $\Longrightarrow \Delta t_L >> \Delta t_R > \Delta t_D$ Longitudinal delay $\Longrightarrow$ cutoff @ 100's MHz	**θ away from θ_{Cher}** $\Longrightarrow \Delta t_L > \Delta t_R > \Delta t_D$ Longitudinal delay $\Longrightarrow$ cutoff @ ~ MHz





Modeling radio emission from particle showers in dense media

Net charge: dense media

- Charge separation due to **geomagnetic field unimportant**.
  (irrelevance of this mechanism checked in ZHAireS simulations).

- Large-E particle interactions in Electromag. showers dominated by:
  - pair production: $\gamma\,\gamma \rightarrow e+\;e-$
  - bremsstrahlung: $e\;\;N \rightarrow e\;\;N\;\;\gamma$

  "electrically neutral" interactions ⇒ *no net charge*

- Low-E (10's of MeV) particle interactions dominated by:
  - Compton: $\gamma\;e-_{atomic} \rightarrow \gamma\;e-$
  - Moeller & Bhabha: $e-\;e-_{atomic} \rightarrow e-\;e-$ & $e+\;e-_{atomic} \rightarrow e+\;e-$
  - e+ annihilation in flight

  interactions "entrain" charge into shower => net charge

G.A. Askaryan

Askaryan effect

Askaryan effect confirmed in experiments at SLAC

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

Main emission mechanism: dense media

- Net negative charge varies in time & space: Q(t,**x**)
  - Q travels with shower front at v ∼ c
  - Q varies in time as number of shower particles:

  first increases & then decreases.
- This variation induces the bulk of radiation:

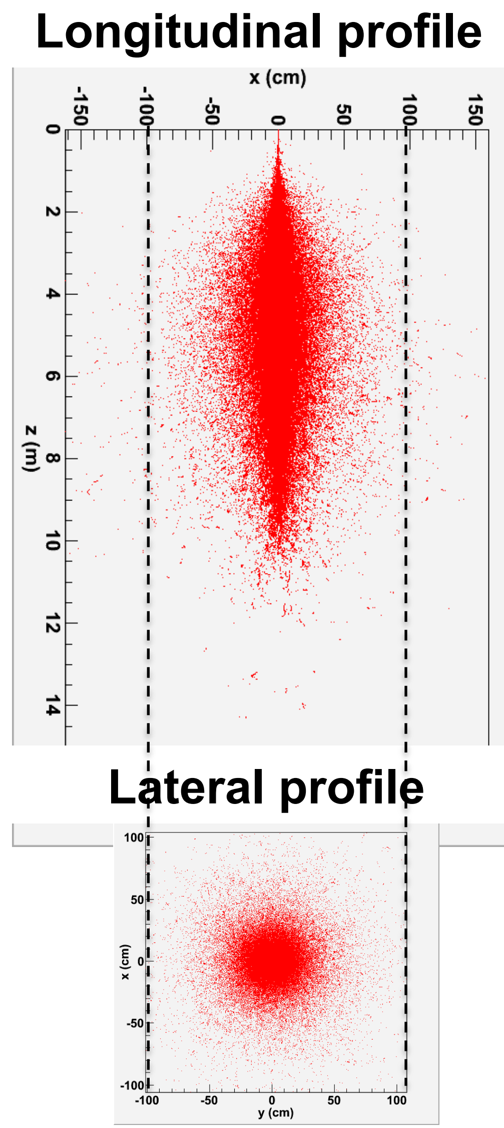
Askaryan current

$$\vec{E}_{\rm Ask} = -\frac{\partial \vec{A}_{\rm Ask}}{\partial t} \propto -\frac{\partial}{\partial t}\left[\int_{-\infty}^{\infty} \frac{\vec{v}_\perp \; Q(\vec{x}', t')}{R} \; \delta\left(t - (t' + \frac{nR}{c})\right) \; d^3\vec{x}'\, dt' \right]$$

Distance
source - observer

$$R = |\vec{x} - \vec{x}'|$$

Relates observer time
(t) to source time (t')
Cherenkov-like effects



- This is known as "**Askaryan radiation**".

Macroscopic modeling of Askaryan radiation in dense media

① Model excess charge Q(t,x,y,z) with:

1. simple approximations
2. input from detailed Monte Carlo simulations

② Apply Maxwell's equations (typically with some approximations) to obtain electric field.

1D "line" model with variable Q(z)

Assumptions:

a. 1D line of current (varying excess charge Q) spreading over length L.
b. Charge varies with depth Q(z) & travels at v > c/n (obtained from MC)

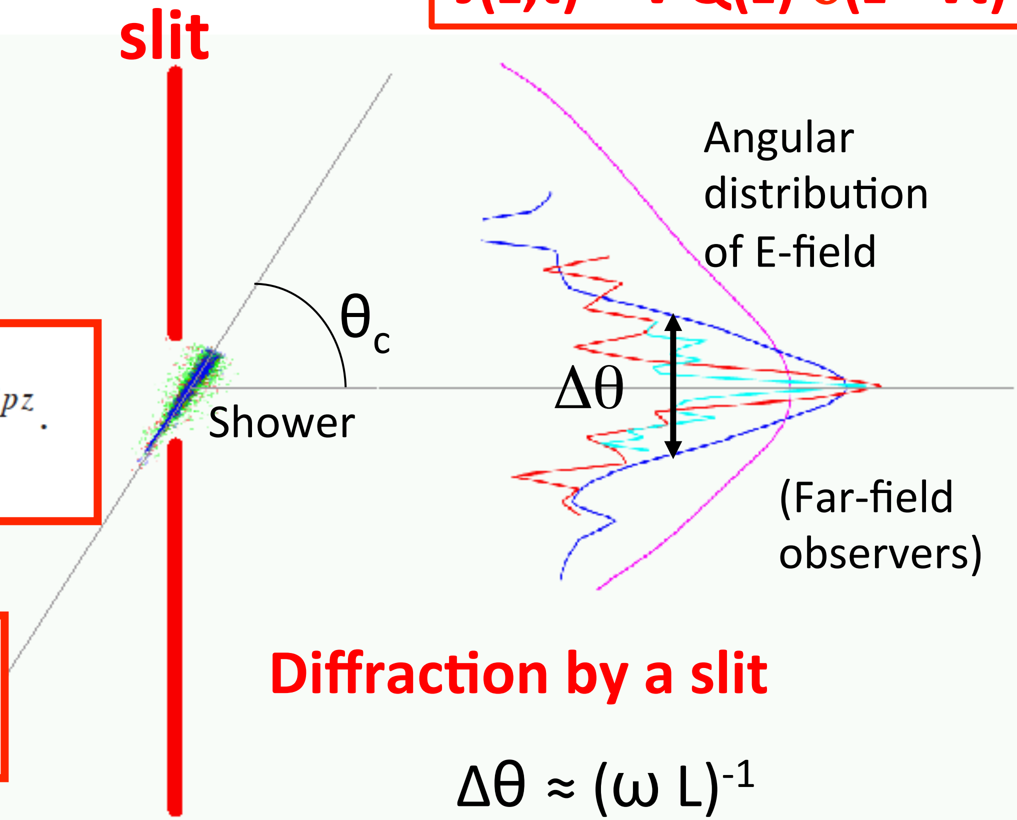
Askaryan radiation Frequency domain:

E-field can be obtained simply Fourier-transforming the longitudinal profile Q(z) of excess charge

$$R|\vec{E}(\omega,\vec{x})| \simeq \frac{e\,\mu_r\, i\omega}{2\pi\epsilon_0 c^2} e^{ikR} \sin\theta \int dz\, Q(z) e^{ipz}.$$

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

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



Diffraction by a slit

$$\Delta\theta \approx (\omega L)^{-1}$$

J. A-M, R.A. Vazquez, E. Zas, PRD **61**, 023001 (1999)
J. A-M & E. Zas, PRD **62**, 063001 (2000)

Askaryan radiation
Time domain:

(Far-field observers)

Current

$$J(z',t') = v\,Q(z')\,\delta(z' - vt')$$

Coulomb gauge

Vector potential

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

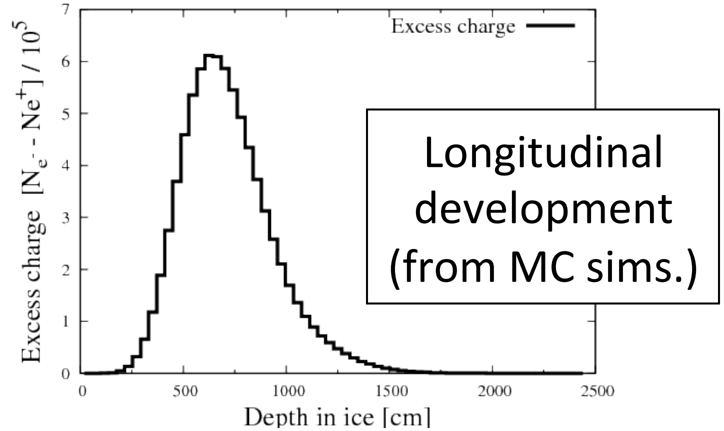
ξ → Retardation + time-compression effects:

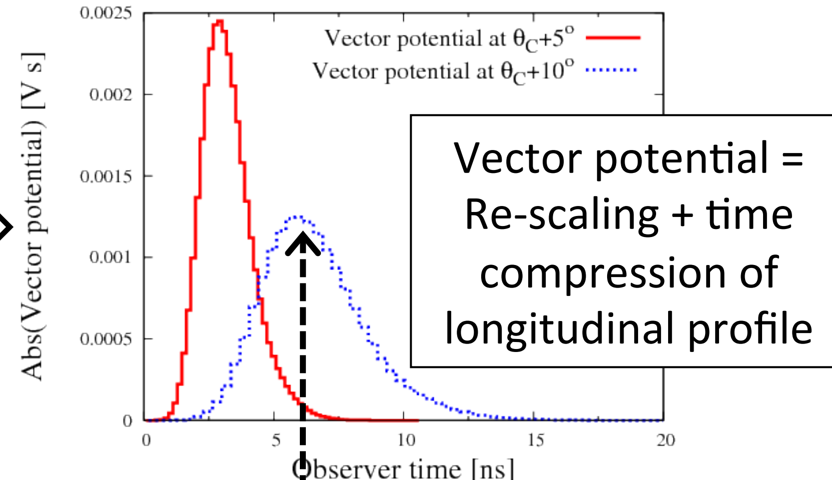
Source position (z') mapped to observer time (t_{obs}) via θ –dependent relation:

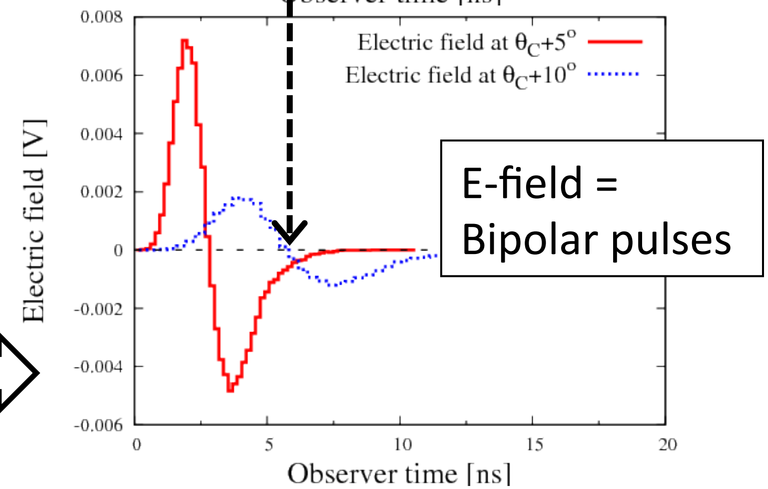
$$t_{obs} = z'(1 - n\cos\theta)/c + t_0 \qquad t_{obs} = t_0 \ @ \ \theta_c$$

Electric field

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







J. A-M, A. Romero-Wolf, E. Zas, PRD **81**, 123009 (2010)

3D model with variable Q(z')

1D macroscopic model fails close to Cherenkov angle where lateral spread (relevant scale) determines the properties of radio emission

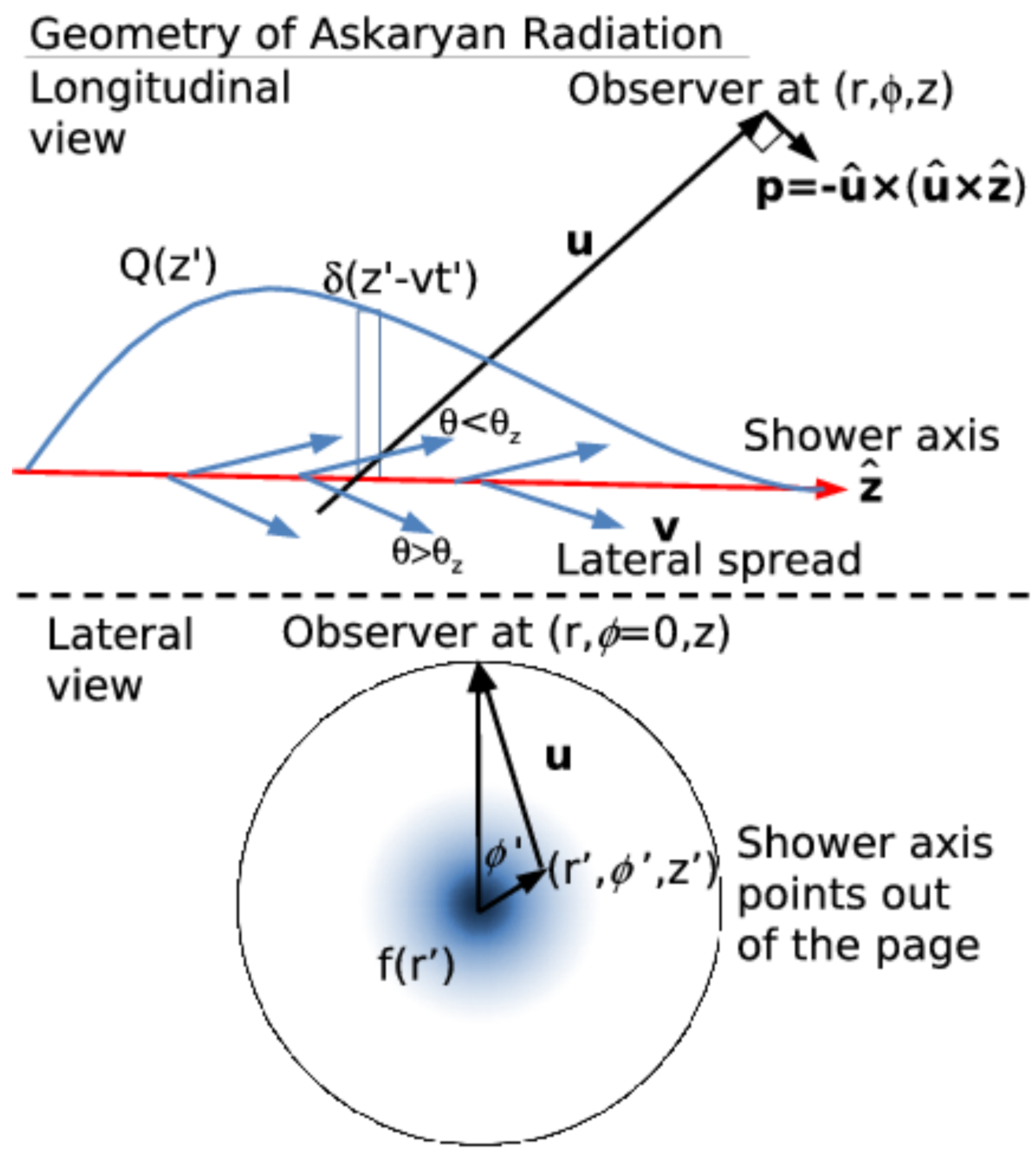
↓ 3D model

"Factorization" of current

Lateral spread

$$J(r', \phi', z', t') = v(r', \phi', z')\, f(r', z') \times Q(z')\, \delta(z' - vt')$$

Longitudinal spread



[J. A-M, A. Romero-Wolf, E. Zas, PRD **84**, 103003 (2011)]

Dealing with the lateral spread:

Lateral spread is difficult to deal with when obtaining vector potential (to say the least …)

$$\mathbf{A}(\theta,t)=\frac{\mu}{4\pi R}\int_{-\infty}^{\infty}dz'Q(z')\int_0^{\infty}dr'r'f(r',z')\times\int_0^{2\pi}d\phi'\frac{\mathbf{v}_\perp(r',\phi',z')}{v}\delta\left(z'\left[\frac{1}{v}-\frac{n\cos\theta}{c}\right]-\frac{nr'\sin\theta\cos\phi'}{c}+\frac{nR}{c}-t\right),$$

However if 2 assumptions are made:

(a) Shape of lateral density depends weakly on depth z′: $f(r',z')\approx f(r')$

(b) Radial velocities depend weakly on depth z′: $v(r',\phi',z')\approx v(r',\phi')$

$$\mathbf{A}(\theta,t)=\frac{\mu}{4\pi R}\sin\theta\underbrace{\int_{-\infty}^{\infty}dz'Q(z')}_{\text{Longitudinal}}\underbrace{\mathbf{F}\left(t-\frac{nR}{c}-z'\left[\frac{1}{v}-\frac{n\cos\theta}{c}\right]\right)}_{\text{Lateral}}$$

"Factorization" of longitudinal & lateral contributions

Form factor

$$\mathbf{F}\left(t-\frac{nR}{c}-z'\left[\frac{1}{v}-\frac{n\cos\theta}{c}\right]\right)=\frac{1}{\sin\theta}\int_0^{\infty}dr'r'\int_0^{2\pi}d\phi'f(r')\frac{\mathbf{v}_\perp(r',\phi')}{v}\times\delta\left(z'\left[\frac{1}{v}-\frac{n\cos\theta}{c}\right]-\frac{nr'\sin\theta\cos\phi'}{c}+\frac{nR}{c}-t\right).$$

J. A-M, A. Romero-Wolf, E. Zas, PRD **84**, 103003 (2011)
form factor introduced first in:
R. Buniy, J.P. Ralston, PRD **65**, 016003 (2001)

“Quasi- universal” form factor from MC simulations:

At Cherenkov angle only lateral spread is relevant

(all shower depths z´are seen at the same time – recall “box “model)

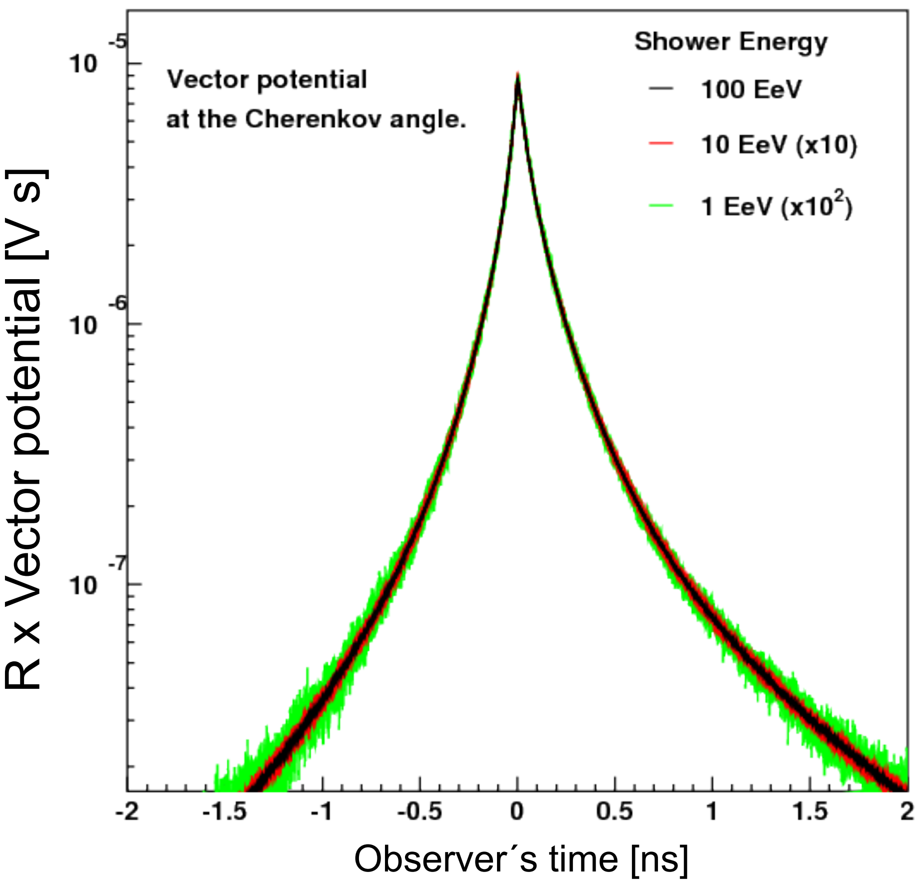
hence, the vector potential is only due to the lateral spread ⟹ form factor

Vector potential at θ_C : obtained in MC sims.

$$\mathbf{A}(\theta_C, t) = \frac{\mu}{4\pi R} \sin\theta_C \mathbf{F}\left(t - \frac{nR}{c}\right) \int_{-\infty}^{\infty} dz' Q(z')$$

Form factor

Shower tracklength: obtained in MC sims.



- **$A(\theta_{Cher}$ t) quasi-universal function**
  - Scales with primary energy
  - Dependence with primary: e, p
- **Asymmetryc due to observer´s position & radial components of velocity**
- **Existing parameterisation.**

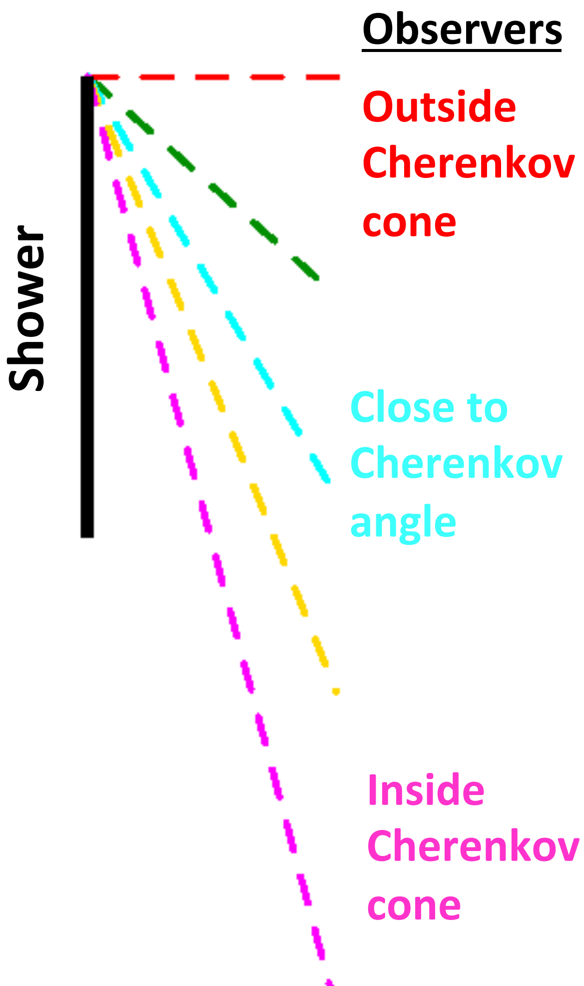
J. A-M, A. Romero-Wolf, E. Zas, PRD **84**, 103003 (2011)

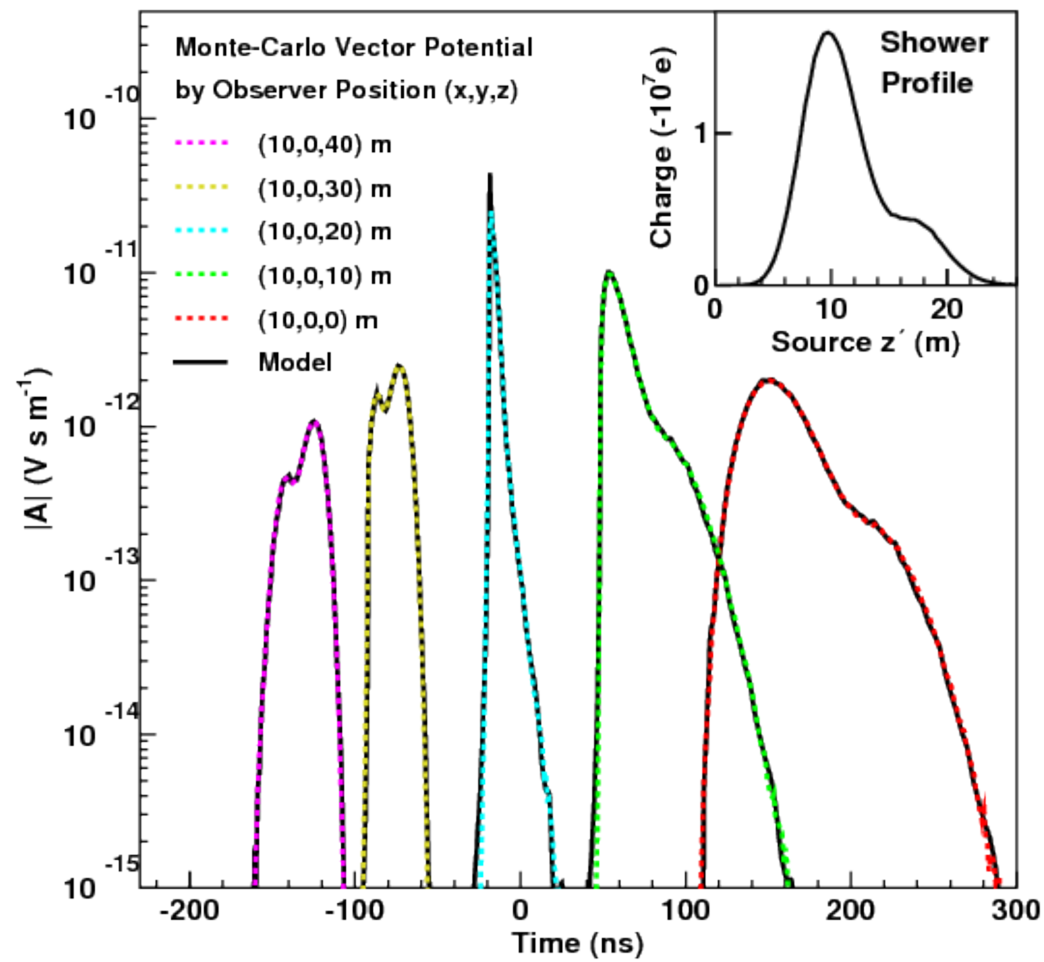
Macroscopic model vs full MC

$$\mathbf{A}(\theta,t)=\frac{\mu}{4\pi R}\sin\theta\int_{-\infty}^{\infty}dz'Q(z')\mathbf{F}\left(t-\frac{nR}{c}-z'\left[\frac{1}{v}-\frac{n\cos\theta}{c}\right]\right)$$

Longitudinal

Lateral (form factor)





Microscopic modeling: Monte Carlo simulations

① Model Q(t,**r**) as a **collection of individual charged particle tracks** using detailed Monte Carlo sims. of shower development

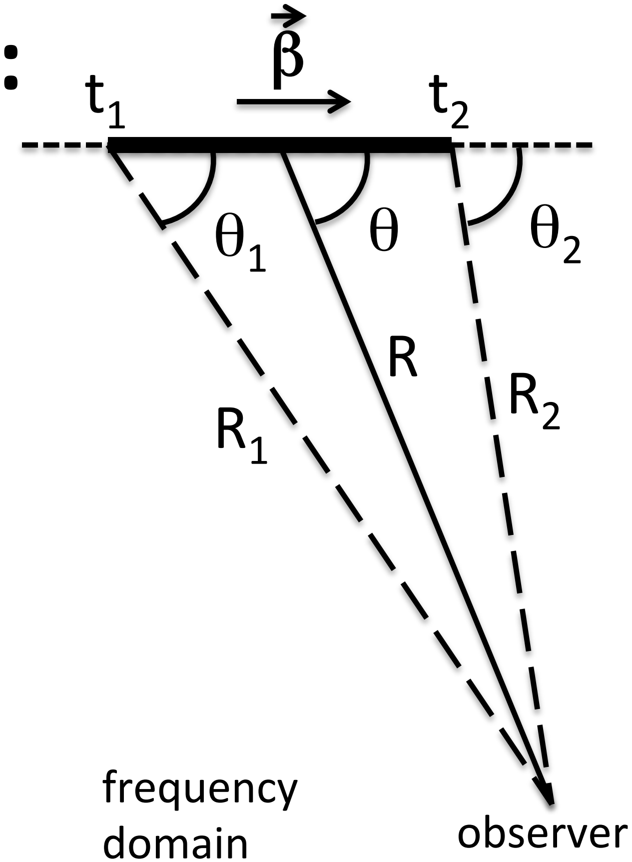
② Obtain **electric field from 1 particle track** from 1st principles.

③ **Add fields** from individual tracks (superposition principle).

- Automatically takes into account interference (coherence effects)

- Approach taken in various **Monte Carlo codes** in dense media:
  - ZHS (Zas-Halzen-Stanev et al.) Zas, Halzen, Stanev PRD **45**, 362 (1992)
  - GEANT3.21 & 4 Razzaque et al. PRD **65** , 103002 (2002), Hussain & McKay PRD **70**, 103003 (2004)
  - ZHAireS (ZHS+Aires) J. A-M, W. R. Carvalho, M. Tueros, E. Zas, Astropart. Phys. **35**, 287-299 (2012)

Field of straight particle track: endpoints & ZHS algorithms



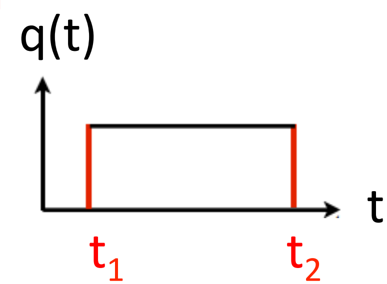
endpoints assumes emission only from instantaneous acceleration/deceleration at end points of track

$$\left|\vec{E}(\omega)\right| = +\frac{q}{c}\left(\frac{e^{ikR_1}}{R_1}\right)\left(\frac{e^{i\omega t_1}}{1-n\beta\cos\theta_1}\right)\beta\sin\theta_1 - \frac{q}{c}\left(\frac{e^{ikR_2}}{R_2}\right)\left(\frac{e^{i\omega t_2}}{1-n\beta\cos\theta_2}\right)\beta\sin\theta_2$$

T. Huege et al., PRE **84**, 056602 (2011)

ZHS starts with current & solves Maxwell's equations in dielectric medium

$$\left|\vec{E}(\omega)\right| = \frac{q}{c}\left(\frac{e^{ikR}}{R}\right)\left(\frac{e^{i\omega(1-n\beta\cos\theta)t_2} - e^{i\omega(1-n\beta\cos\theta)t_1}}{1-n\beta\cos\theta}\right)\beta\sin\theta$$



E. Zas, F. Halzen, T. Stanev PRD **45**, 362 (1992)

$$\mathbf{J}(\mathbf{x}, t) = -e\mathbf{v}\delta^{(3)}(\mathbf{x}-\mathbf{x_0}-\mathbf{v}t)\Theta(t-t_1)\Theta(t_2-t)$$

Pros & cons

endpoints

$$\left|\vec{E}(\omega)\right| = +\frac{q}{c}\left(\frac{e^{ikR_1}}{R_1}\right)\left(\frac{e^{i\omega t_1}}{1-n\beta\cos\theta_1}\right)\beta\sin\theta_1 - \frac{q}{c}\left(\frac{e^{ikR_2}}{R_2}\right)\left(\frac{e^{i\omega t_2}}{1-n\beta\cos\theta_2}\right)\beta\sin\theta_2$$

- ✓ Handles near-field kR ~ 1
- x Infinite at Cherenkov angle
- x Tends to a constant term for ω ⟶ 0
- • Existing algorithm also in time-domain

ZHS

$$\left|\vec{E}(\omega)\right| = \frac{q}{c}\left(\frac{e^{ikR}}{R}\right)\left(\frac{e^{i\omega(1-n\beta\cos\theta)t_2} - e^{i\omega(1-n\beta\cos\theta)t_1}}{1-n\beta\cos\theta}\right)\beta\sin\theta$$

- x Valid as long as kR >>1
- ✓ Finite limit at Cherenkov angle.
- ✓ Tends to 0 for ω ⟶ 0 (bipolar pulses)
- • Existing algorithm also in time-domain

Several facts:

- ✓ Both give the same result in the far-field:
  $1/R_1 = 1/R_2 = 1/R$ & $kR_1 = kR$ & $kR_2 = kR - kc\beta\,(t_2-t_1)\cos\theta$
- x endpoints uses ZHS formula close to Cherenkov angle to avoid infinities
- ✓ ZHS limit at Cherenkov angle validated with exact calculation (see next slide)
- ❑ SLAC T510 experiment (talks A. Zilles & K. Mulrey)) testing the two algorithms.

Validation of ZHS algorithm: comparison to Exact field calculation

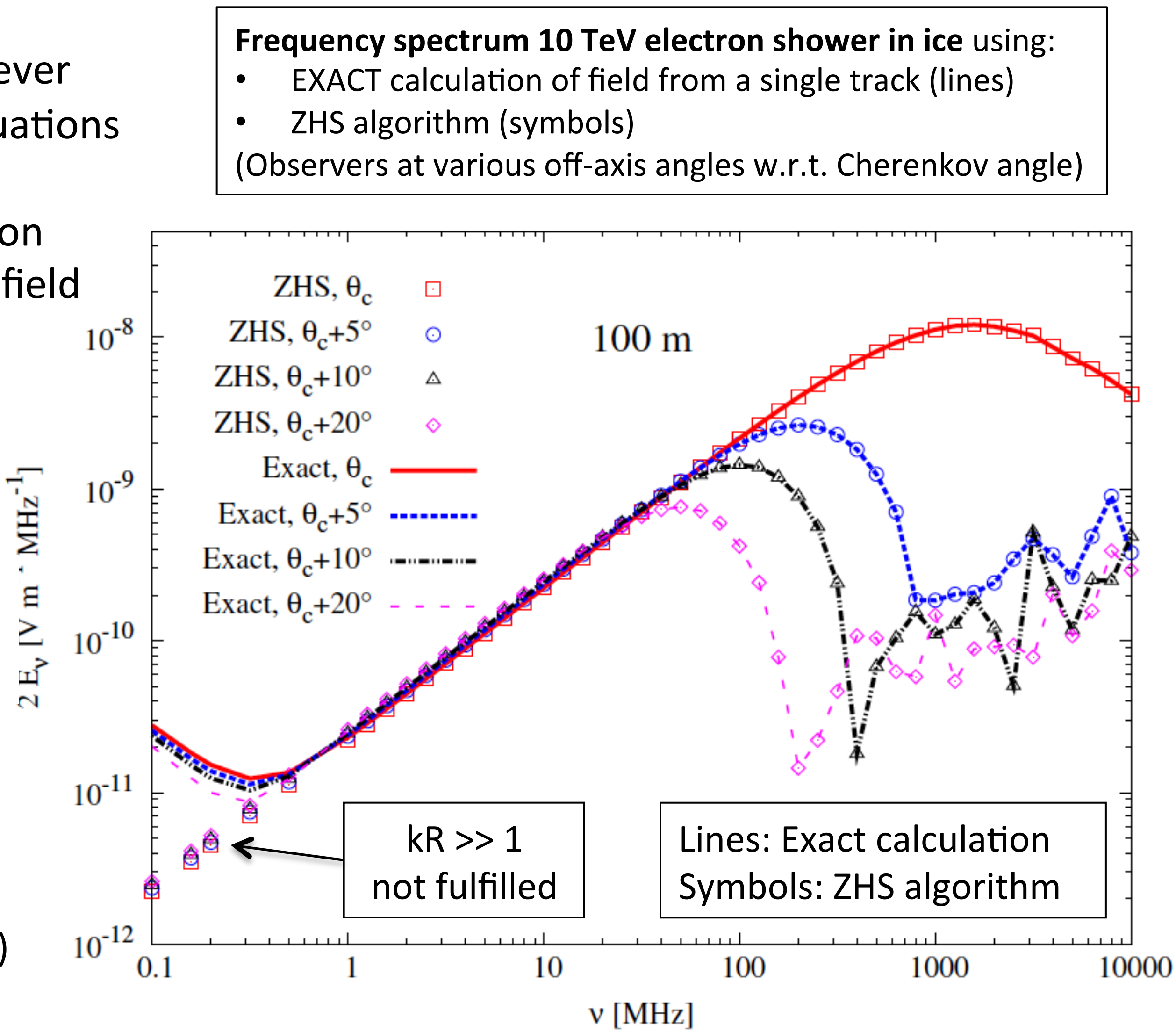
Exact field calculation:

- ✓ No approximations whatsoever when solving Maxwell's equations for a single straight track.
  - – No far-zone limitation
- ✓ Accounts for all features of field

Better than 1% agreement as long as observer is in far-field zone: $kR \gg 1$

$$kR \sim 3.7\left(\frac{\nu}{100\ \mathrm{MHz}}\right)\left(\frac{R}{1\ \mathrm{m}}\right) \gg 1.$$

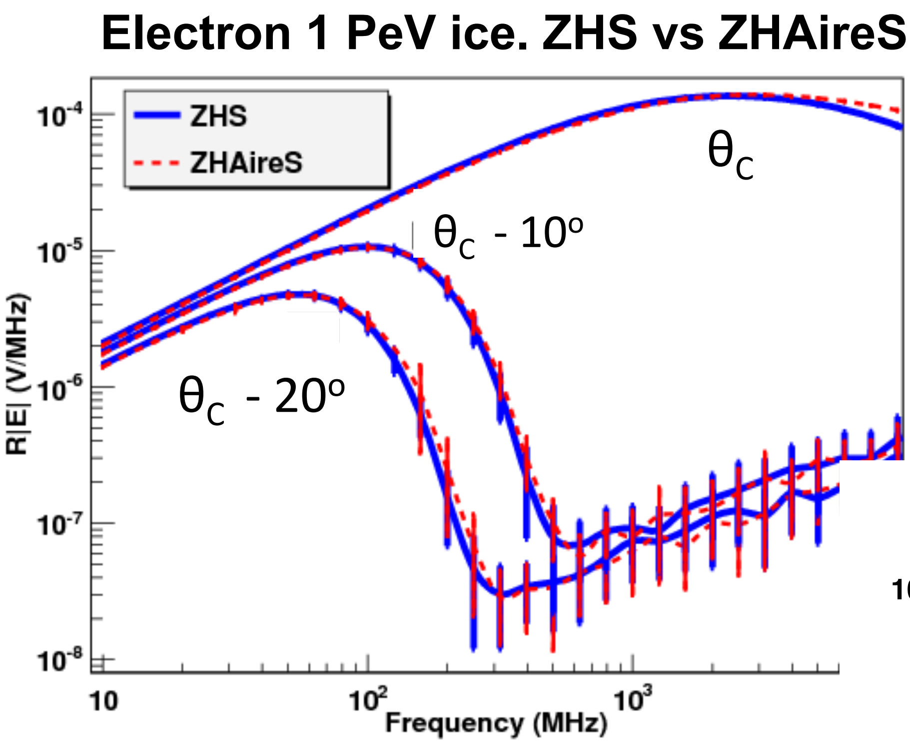
Aside: For a very long (infinite) track, ZHS algorithm reproduces analytical Cherenkov formula (see paper below & backup slide)

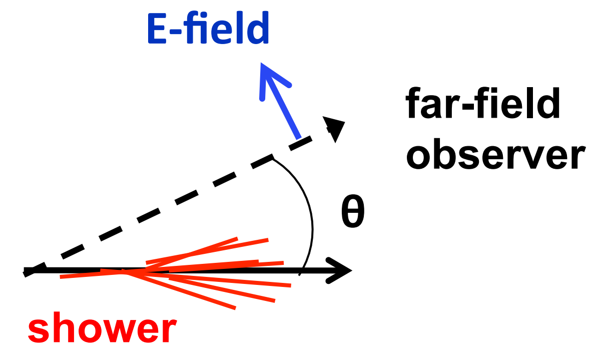


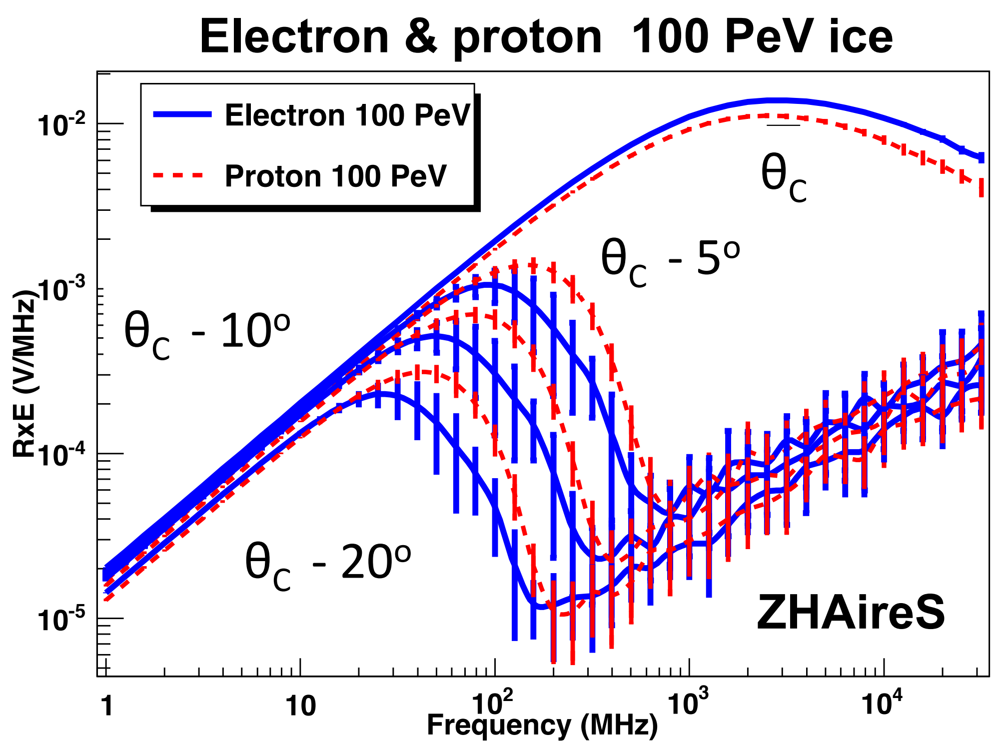
D. García-Fernández, J.A-M, W. R. Carvalho, A. Romero-Wolf, E. Zas, PRD **87**, 023003 (2013)

A few example results of microscopic modeling (ice)

Askaryan radiation: Frequency spectrum



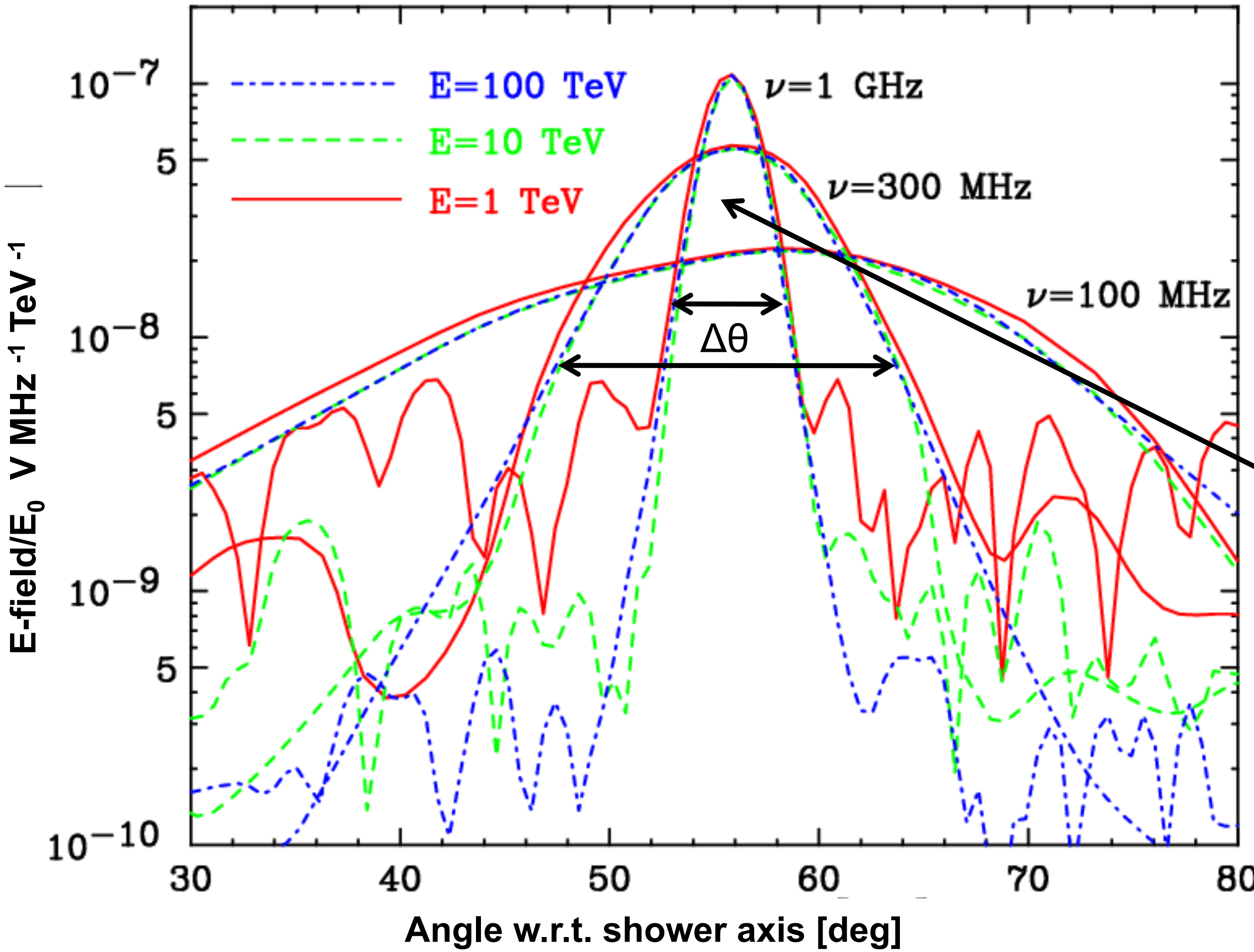




- Microscopic models allow studies of proton electron & ν-induced showers including the LPM effect.
- Cut-off frequencies roughly as predicted by simplest models.

J. A-M, W. R. Carvalho, M. Tueros, E. Zas, Astroparticle Physics **35**, 287-299 (2012)

Angular pattern: diffraction effects



(Far-field observers)

Cherenkov peak

$\Delta\theta \approx (L\omega)^{-1}$

in agreement with 1D model

ZHS ice

E. Zas, F. Halzen, T. Stanev, PRD 45, 162 (1992),
J. A-M & E. Zas, PLB 411, 218 (1997)

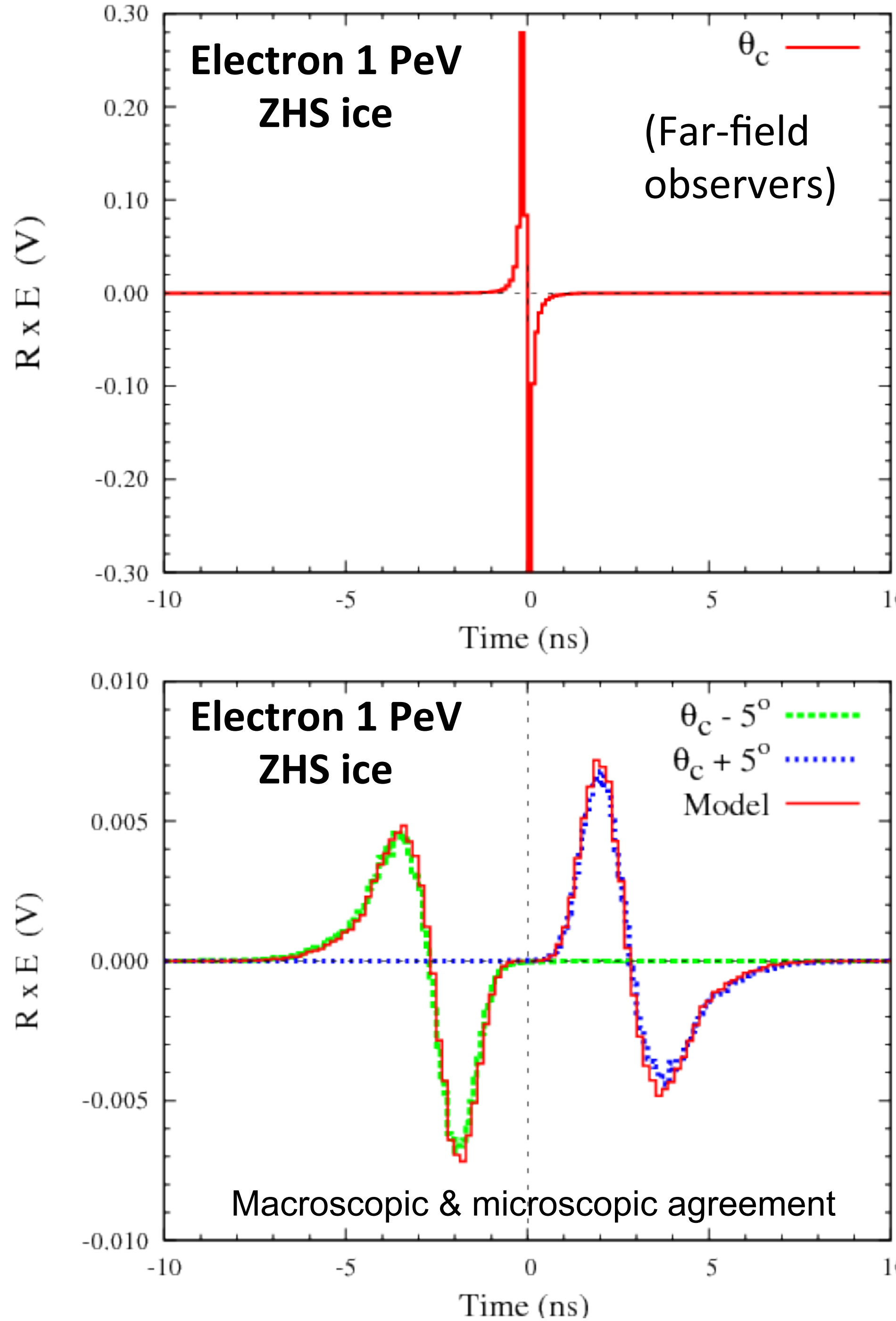
Askaryan radiation Time domain MC

Narrow nano-second signal at Cherenkov angle

Time duration increases as observer moves away from θ_c

Relativistic effects apparent: Time reversal inside & outside Cherenkov cone: pulses are reflections of each other.

… as expected from simple models.



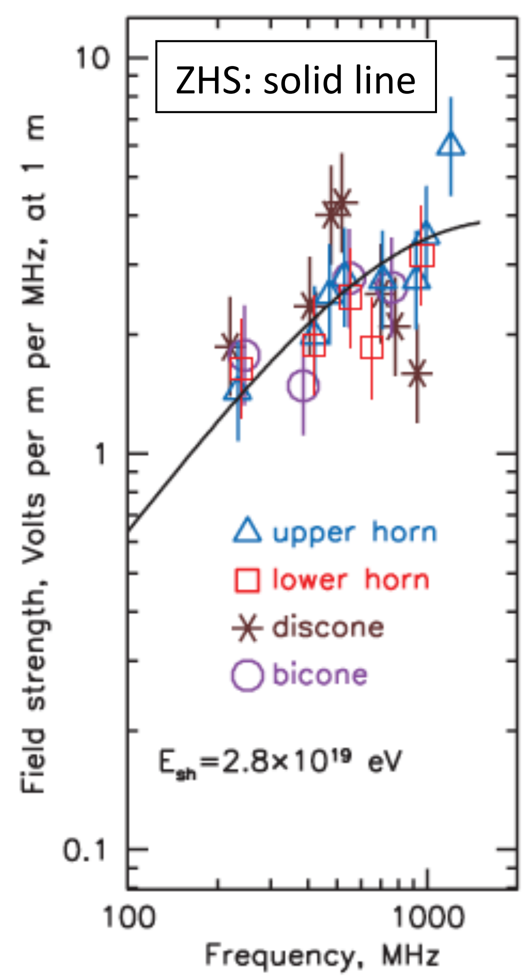
[J. A-M, A. Romero-Wolf, E. Zas, PRD **81**, 123009 (2010)]

Models & SLAC data: sand, salt, ice

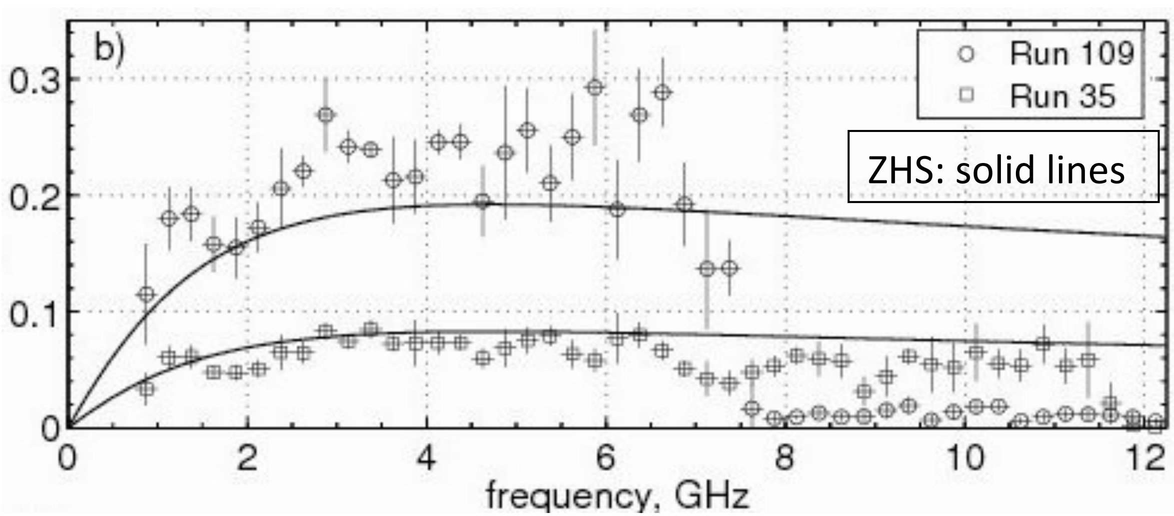
Bunches of ~ GeV bremss. γ dumped in sand & salt & ice: $E_0 \sim 6 \times 10^{17} - 10^{19}$ eV .

- Askaryan effect seen.
- Linearly polarized signal.
- Power in radio waves goes as Energy squared
- Bipolar pulses in time-domain

Frequency spectrum (Ice)



Frequency spectrum (Salt)

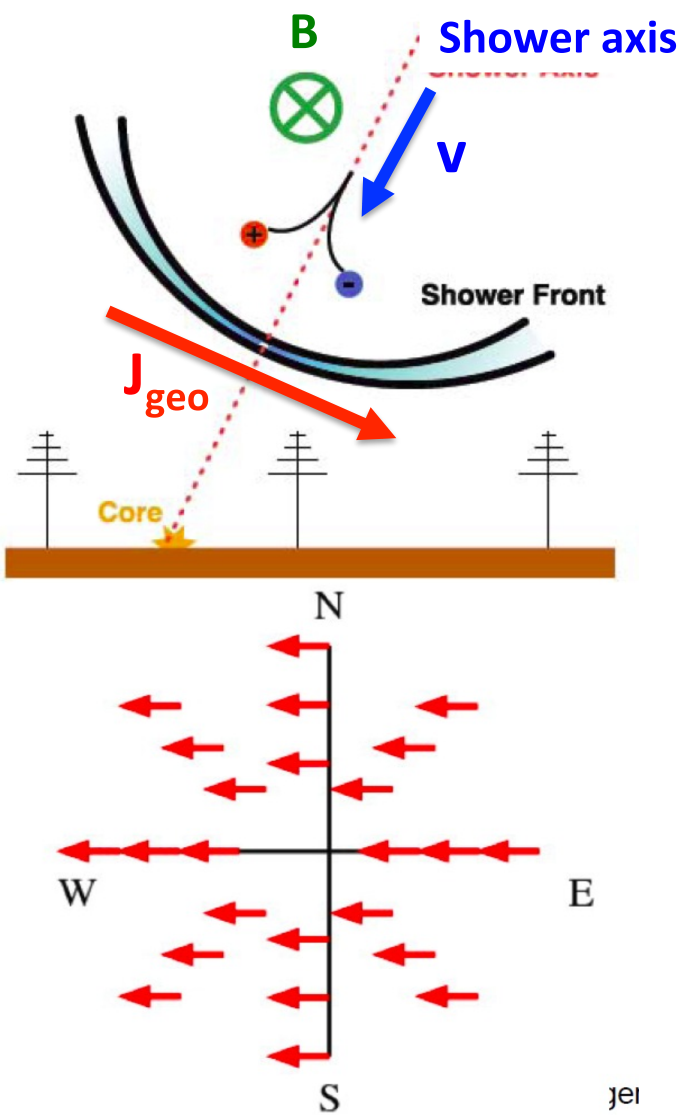


D. Saltzberg et al. PRL **86** (2001);
P. Gorham et al. PRD **72** (2005) 023002
P.Miocinovic et al. PRD **74** (2006),
P. Gorham et al. PRL **9**9 (2007)

See also SLAC T-510 experiment (talks Mulrey & Zilles)

Modeling radio emission from particle showers in air

Net charge: Geomagnetic mechanism



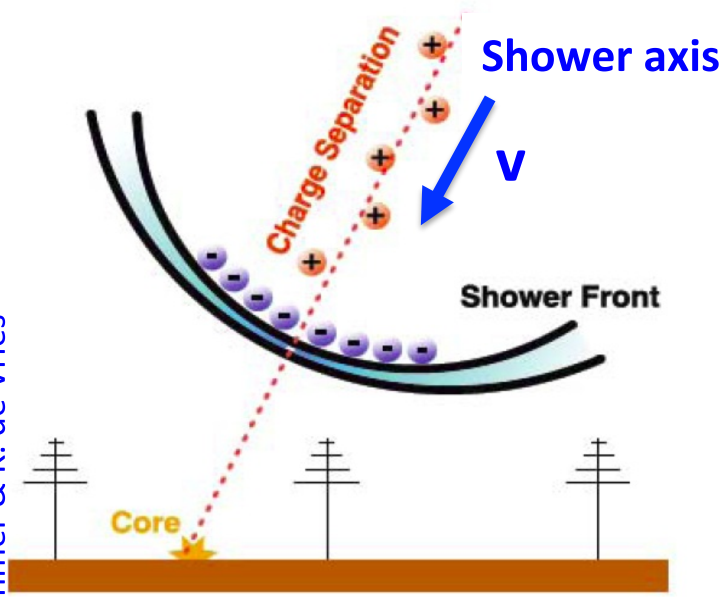
Diagrams H. Schoorlemmer & K. de Vries

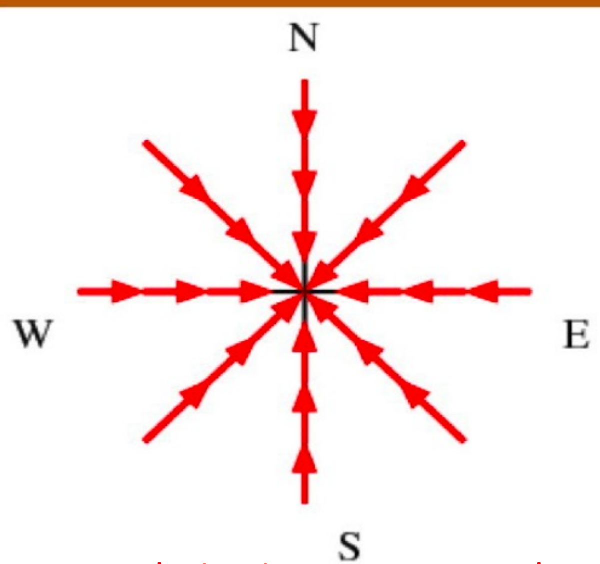
Approx. polarization pattern on shower plane

- Separation of e- & e+ in magnetic field of Earth.
- Induces drift electric current (J_{geo}) approx. perpendicular to shower axis (v) and magnetic-field (B) i.e. parallel to (v x B)
- Current travels with shower front & varies in time as number of particles:
  - this induces the bulk of radiation.
  - responsible for bi-polar pulses
- Electric field:
  - magnitude ~ B sinα (α = angle between **B** and **v**)
  - approx. polarized along direction of Lorentz force: v x B

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

Charge-excess (Askaryan) mechanism





Diagrams H. Schoorlemmer & K. de Vries

Approx. polarization pattern on shower plane

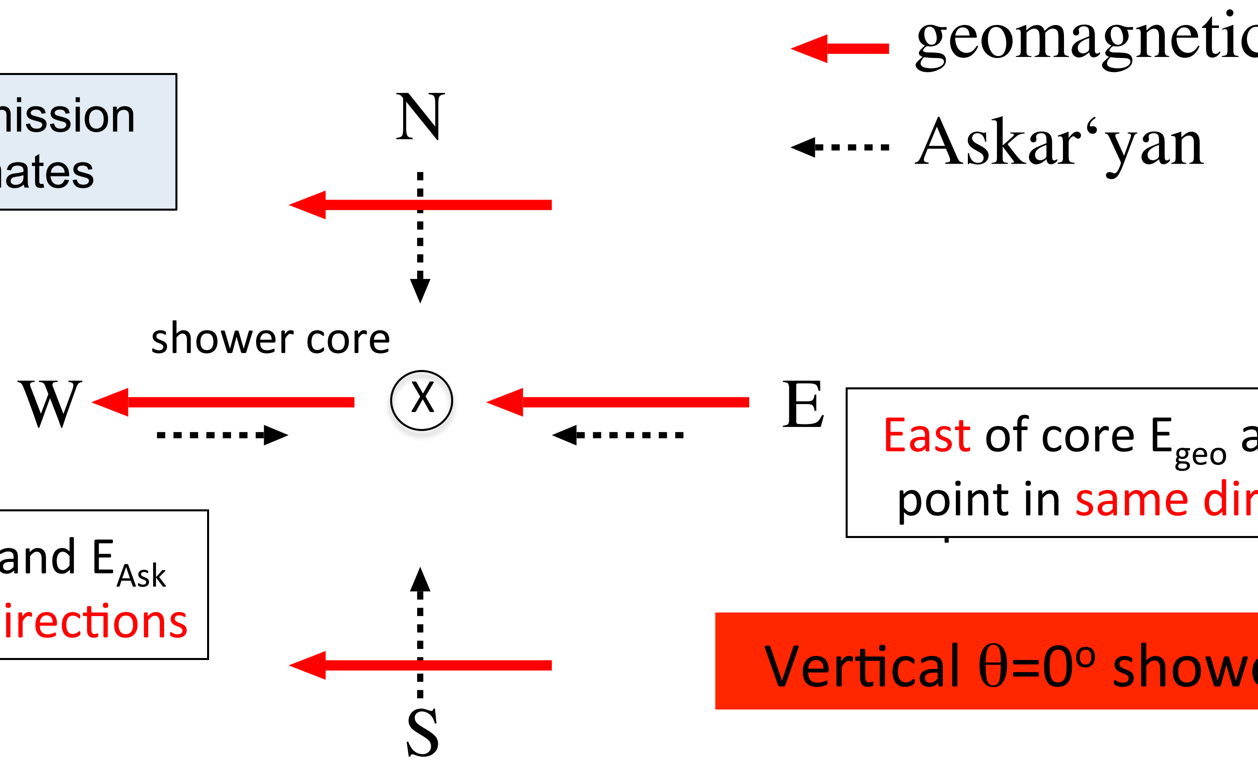
- As shower develops, it drags atomic e- of atmosphere that "entrain" into shower, mainly due to Compton scattering of shower photons: γe-(atomic) ⟶ γe-
  - ~ 20-30 % of excess e- induced
- Induces electric current (**J_{Ask}**) approx. along shower axis (v).
- Current travels with shower front & varies in time as excess of e-:
  - this induces bulk of radiation due to charge excess.
  - bi-polar pulses
  - can become dominant if shower axis is parallel to magnetic field
- Electric field approx. polarized perpendicular to axis **v** (i.e. radial)

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

Interference between both mechanisms

Vectorial addition of geomagnetic and charge-excess fields induces asymmetries in total electric field

Geomagnetic emission typically dominates



East of core E_{geo} and E_{Ask} point in same direction

West of core E_{geo} and E_{Ask} point in opposite directions

Vertical $\theta=0^{o}$ shower

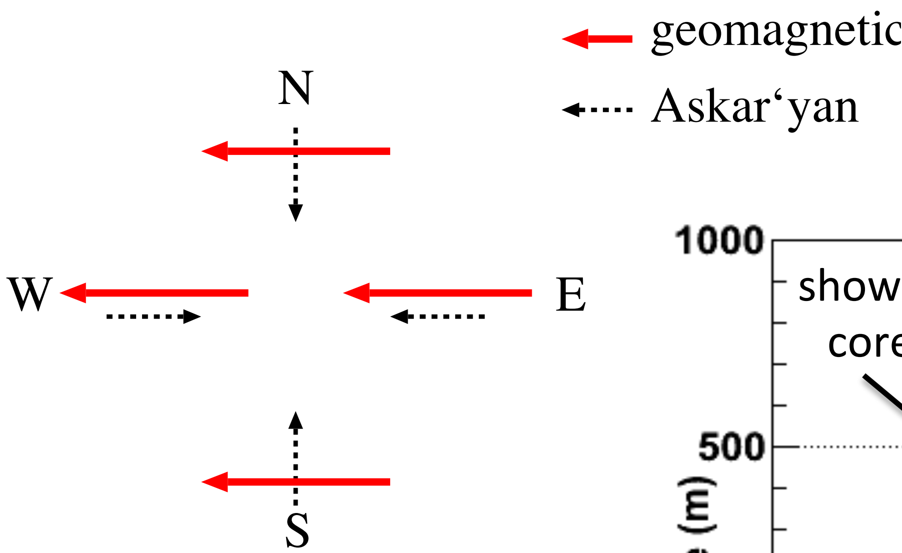
Approx. polarization pattern on shower plane

Paradigm tested with MC simulations: see J.A-M et al. talk at this meeting

K. Werner, O. Scholten, Astroparticle Phys. **29**, 393 (2008)

Asymmetries in the Lateral Distribution of radio signal

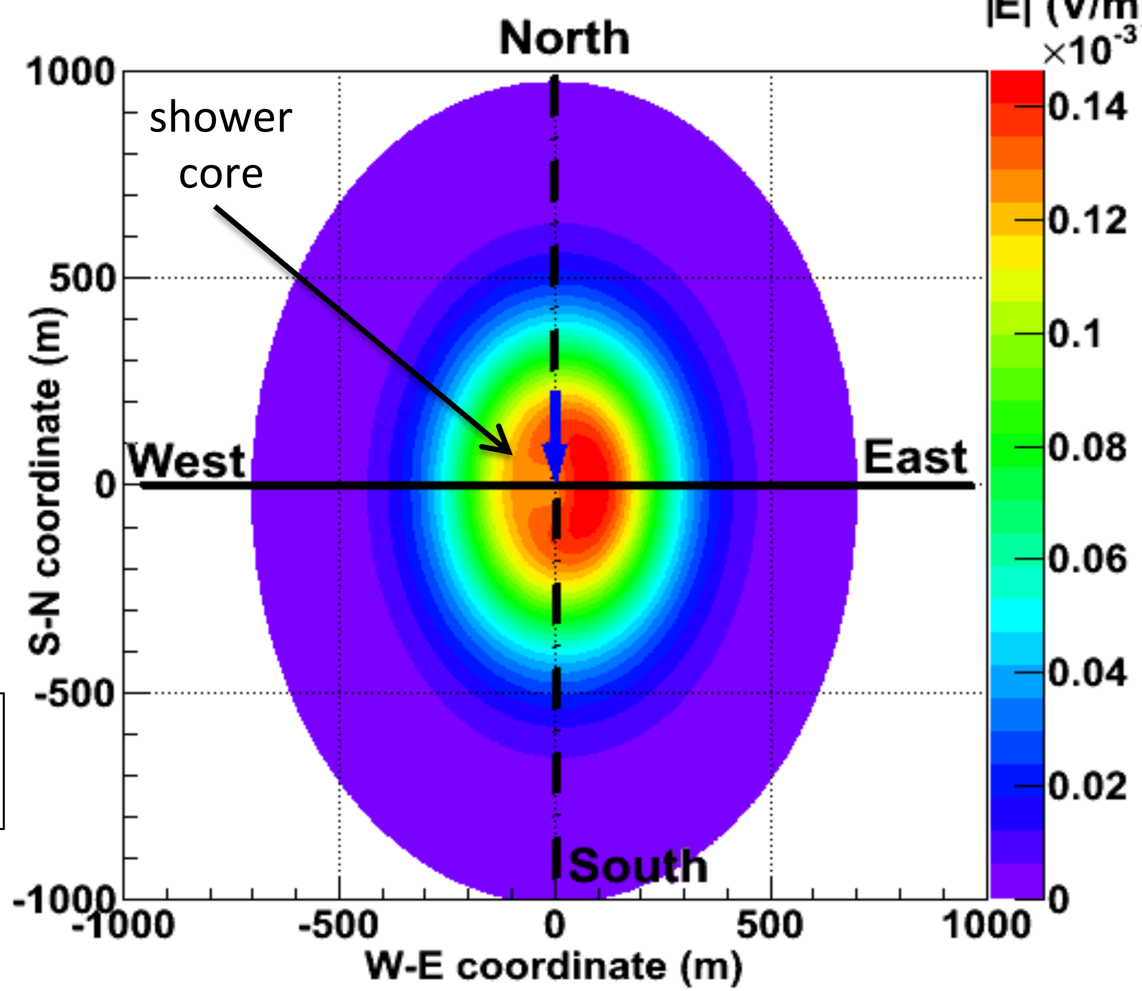
ZHAireS simulations



1-dimensional function cannot describe complex pattern of signals |E| depends on r and ϕ (azimuthal angle of observer)

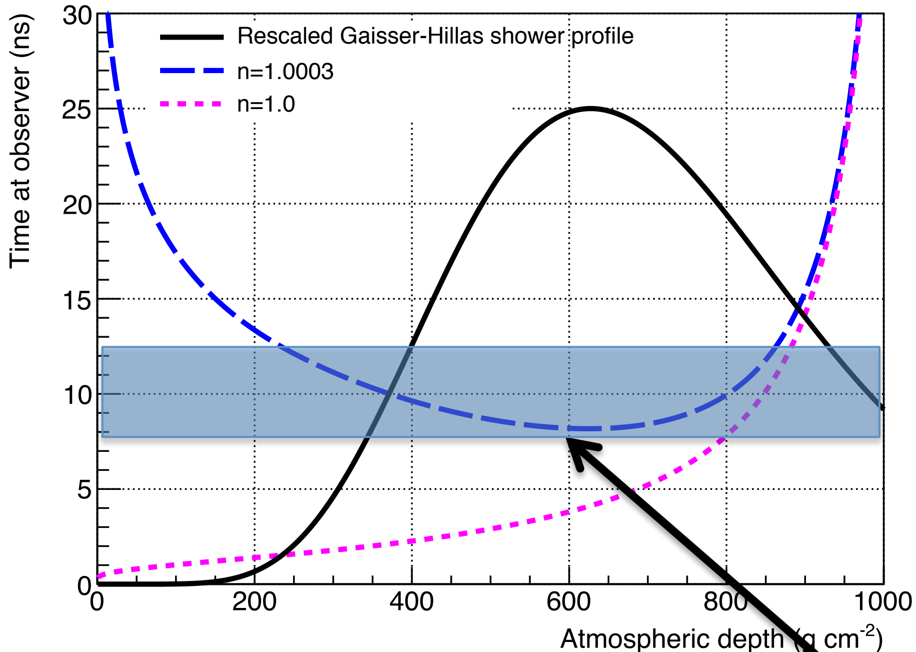
2-dimensional pattern of electric field modulus on ground

Proton, 10^{17} eV, 45°
arriving from North LOFAR site

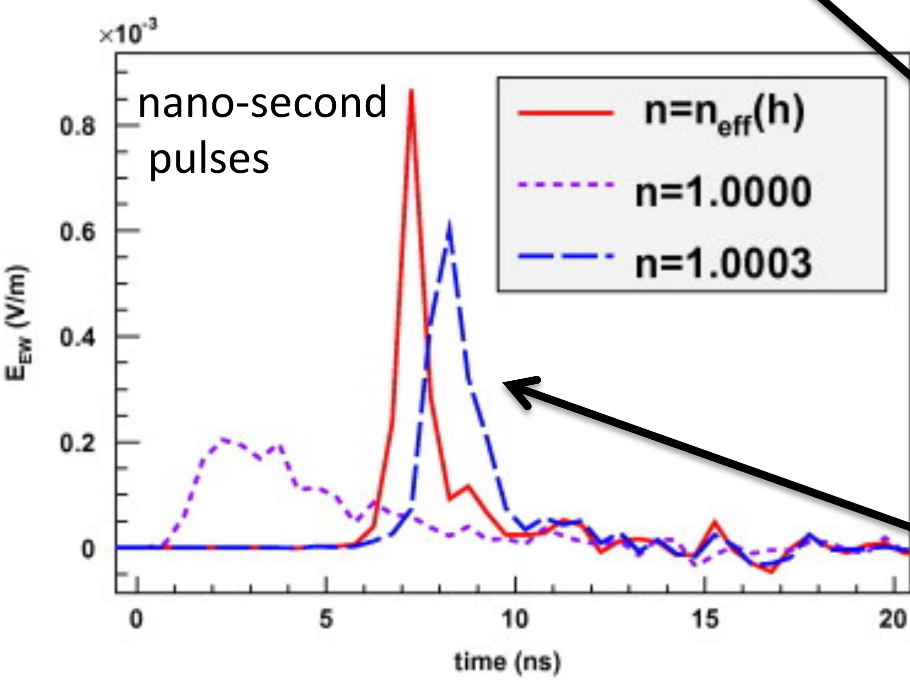


J. A-M, W.R. Carvalho Jr., E. Zas, Astropart. Phys. 35 (2012) 325

Cherenkov-like phenomena



- Relativistic effects play a crucial role in emission.
- Stem from the fact that refractive index of air n > 1 (~ 1.000325 at sea level)
- Shower particles (E> few MeV) travel faster than radio waves:



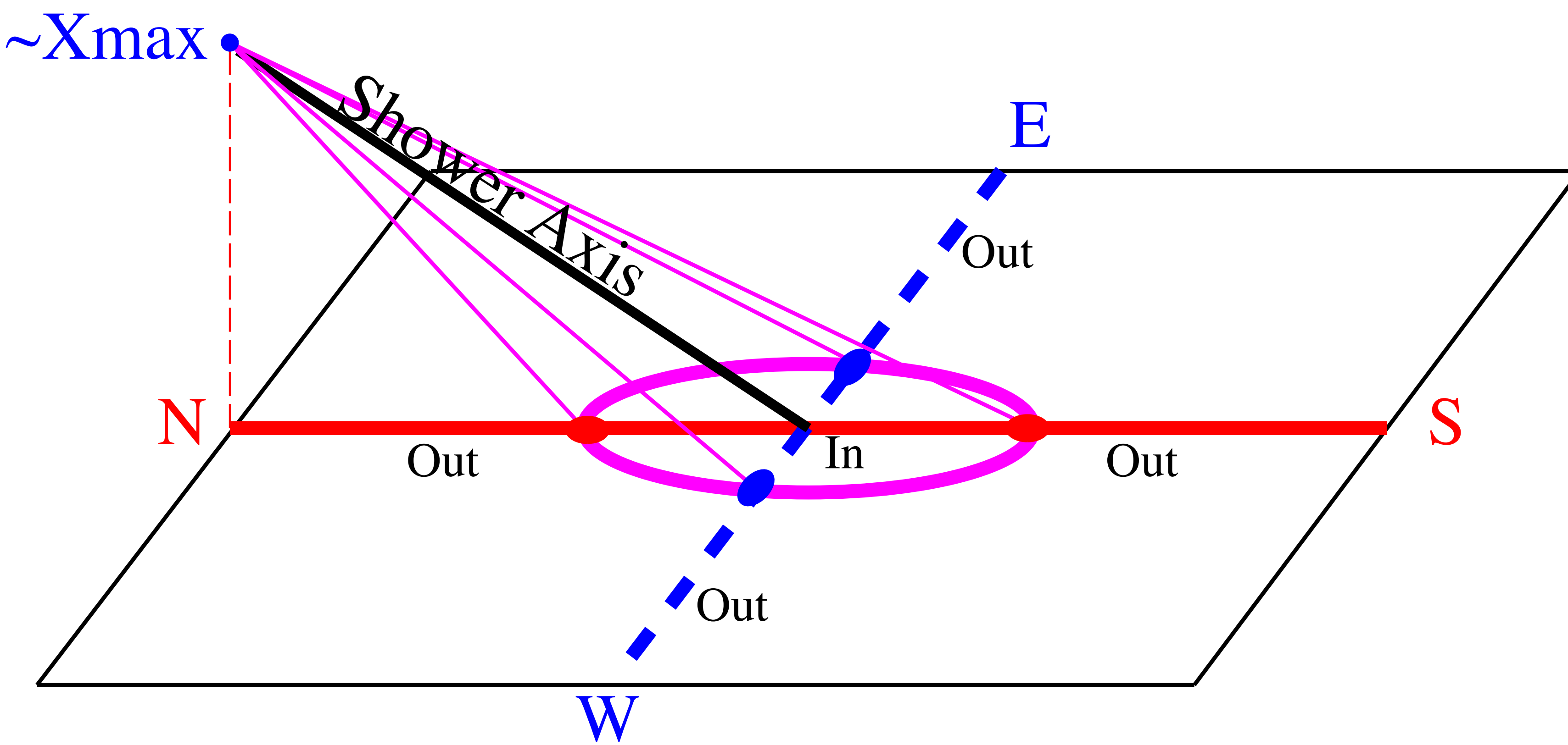
Waves from different parts of shower development can arrive simultaneously at observer

This observer "sees" wide region around shower max. in just a few ns

⇓

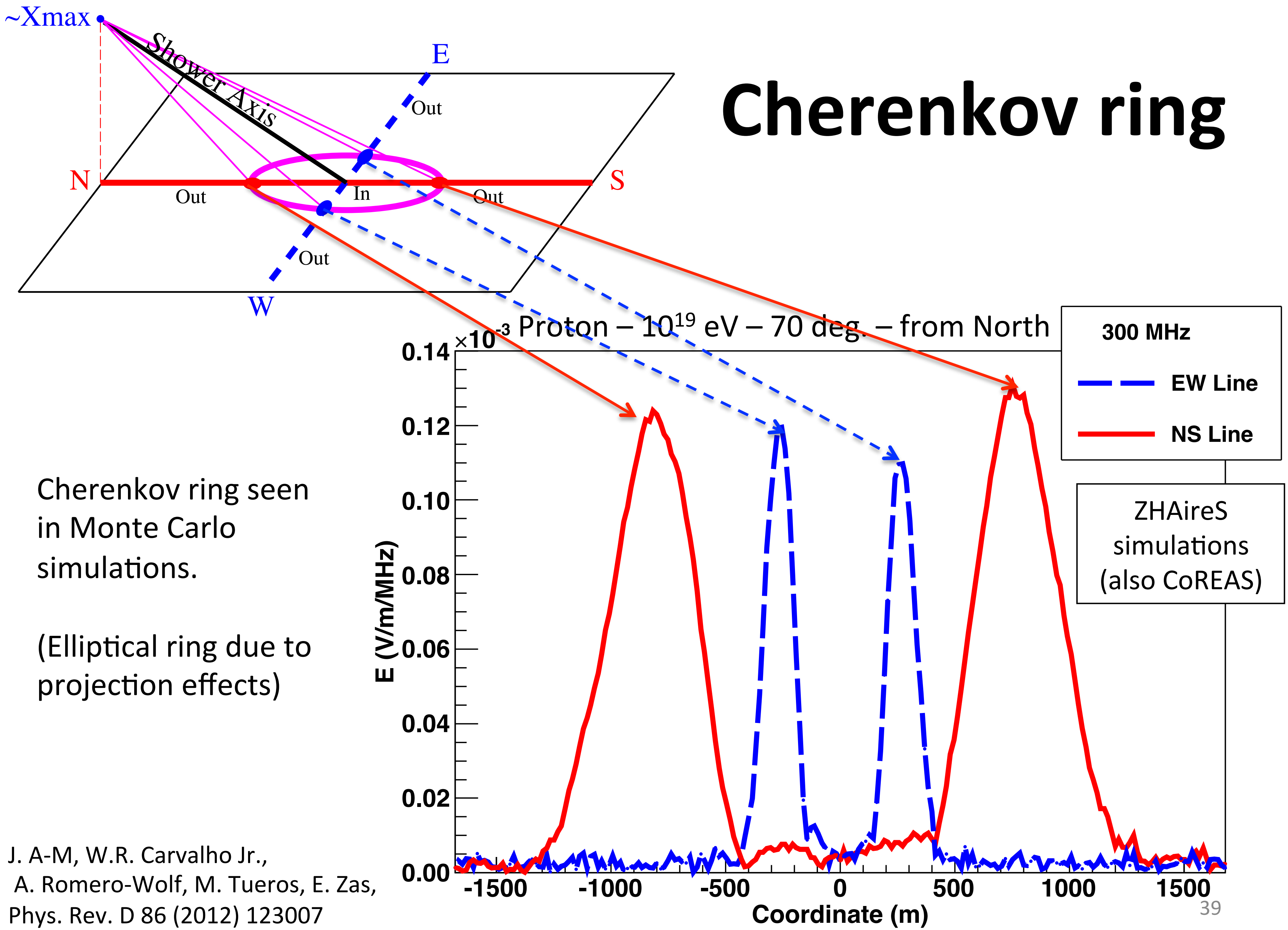
Time-compression boosting emission. High Frequency components up to GHz

Cherenkov ring



Amplitude of electric field largest for observers viewing depth of maximum (X_{max}) at Cherenkov angle ($\sim$ 1 deg.) $\longrightarrow$ induces Cherenkov ring

Cherenkov ring



ZHAireS simulations (also CoREAS)

Cherenkov ring seen in Monte Carlo simulations.

(Elliptical ring due to projection effects)

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

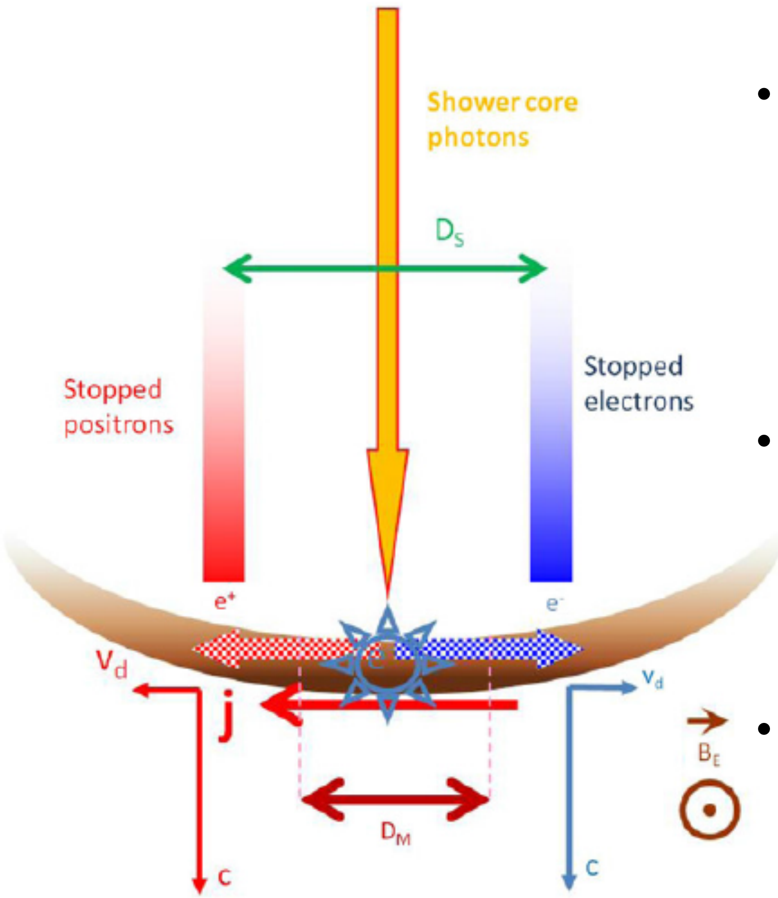
Modern models and Monte Carlo codes (Air)

more „microscopic"

MGMR	time-domain, analytic, parametrized shower, fast, free parameters, summing up „mechanisms"
EVA	time-domain, parameterisation of distributions derived from cascade equations or MC
SELFAS2	time-domain, shower from universality, summing up vector potentials for tracks
REAS3.1	time-domain, histogrammed CORSIKA showers, endpoint formalism
ZHAireS	time- and frequency-domain, Aires showers, ZHS formalism Also works in dense dielectric media
CoREAS	time-domain, CORSIKA showers, endpoint formalism

T. Huege

Macroscopic GeoMagnetic Radiation Model (MGMR)



O. Scholten, K. Werner, F. Rusdyi, Astroparticle Phys. **29**, 94 (2008)

- **Analytic approach** – simplified macroscopic description of (**point-like**) currents in space & time with input from MC simulations.

- Model for **transverse** current induced by Earth's magnetic field:

$$j(x,y,z,t) = \underbrace{\langle v_d q \rangle}_{\text{drift velocity}} \overbrace{e N_e f_t(t_r)}^{\text{longitudinal profile}}.$$

- **<u>Time variation of current</u>** induces bulk of emission:

$$E_x(t,d) \approx J \frac{c^2 t_r^2 4}{d^4} \left[t_r \boxed{\frac{\mathrm{d} f_t(t_r)}{\mathrm{d} t_r}} + f_t(t_r) \right]$$

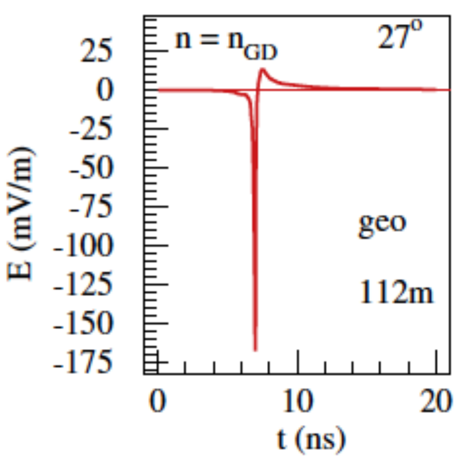
at large distances to core

- **Other contributions** (in order of relevance):
  - Time-variation of **charge-excess** longitudinal current.
  - Moving Geomagnetic current itself.
  - Dipole momentum moving with shower front.
  - Charged plasma "left behind" by shower: at rest but increases as shower develops ⇒ radiates

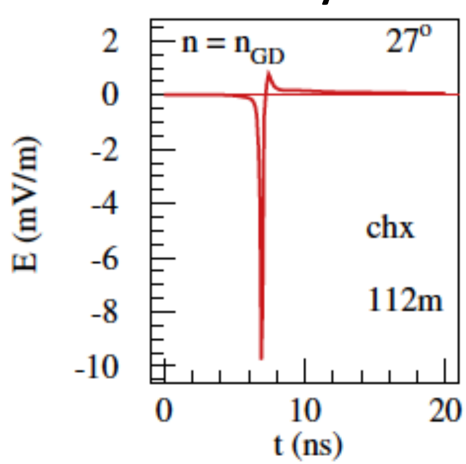
Electric fields using Variable *n* in Air (EVA)

- More precise currents in space & time from MC sims. of shower development (CONEX + B field)
- **Smooth parameterizations** of currents to perform semi-analytic calculations of fields: geomagnetic & Askaryan contributions.
- Realistic refractive index n(h): Cherenkov-like phenomena

Geomagnetic

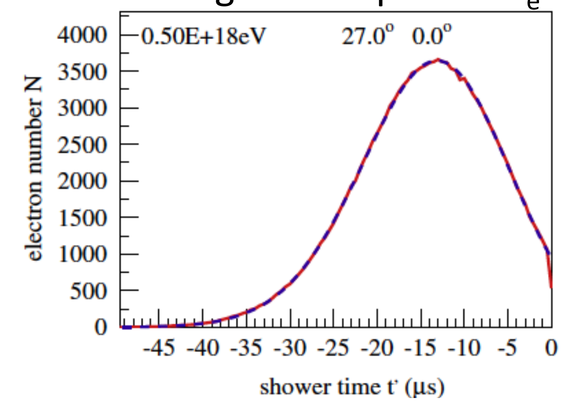


Askaryan

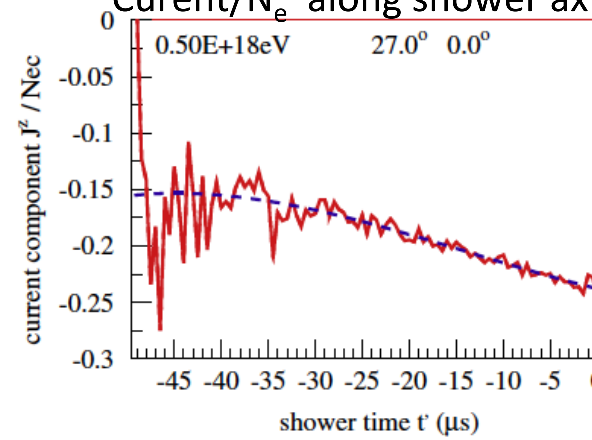


K. Werner, K.D. de Vries, O. Scholten, Astroparticle Phys. **37**, 5 (2012)

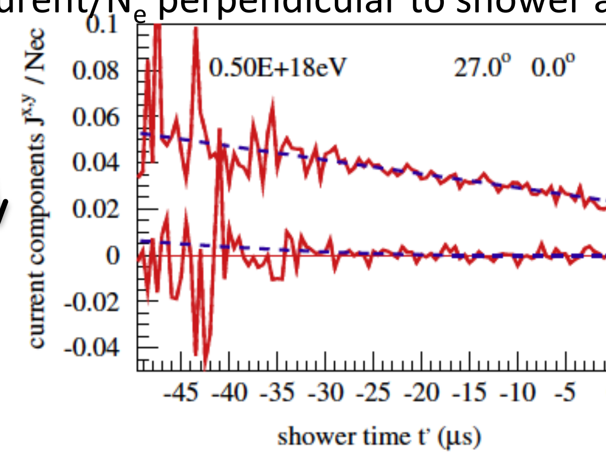
Longitudinal profile N_e



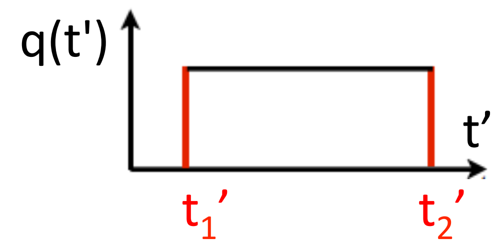
Curent/N_e along shower axis



Curent/N_e perpendicular to shower axis

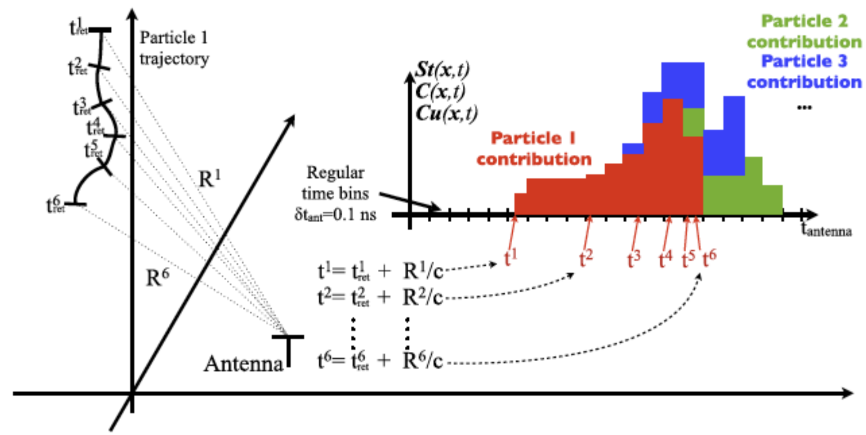


Simulation of Electric Field in Air Showers (SELFAS)



Current for single track

- Shower sampled from universal distributions:
  - GIL Longitudinal profile, energy distribution, momentum direction, lateral distribution, delay time (shower front thickness), charge excess
- Sample e+ and e- of shower front (3D)
- Track each e+/e- along their trajectory:
  - magnetic field deflection
  - energy loss
  - multiple scattering
- Calculate field of each track



- Sum up all individual fields at any space-time observer position

$$\boldsymbol{E}_{tot}(\boldsymbol{x},t) = \frac{1}{4\pi\epsilon_0}\left\{\sum_{i=1}^{\zeta}\left[\frac{\boldsymbol{n}_i q_i(t_{ret})}{R_i^2(1-\boldsymbol{\beta}_i\cdot\boldsymbol{n}_i)}\right]_{ret} + \frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}^{\zeta}\left[\frac{\boldsymbol{n}_i q_i(t_{ret})}{R_i(1-\boldsymbol{\beta}_i\cdot\boldsymbol{n}_i)}\right]_{ret} - \frac{1}{c^2}\frac{\partial}{\partial t}\sum_{i=1}^{\zeta}\left[\frac{\boldsymbol{v}_i q_i(t_{ret})}{R_i(1-\boldsymbol{\beta}_i\cdot\boldsymbol{n}_i)}\right]_{ret}\right\}$$

Static contribution

Time variation of excess charge

Time variation of geomagnetic current

V. Marin, B. Revenu, Astroparticle Phys. **35**, 733 (2012)

CoREAS & ZHAireS

- **Microscopic models** for the calculation of radio emission from EAS
  - Particles tracked in full shower Monte Carlo simulations

- Superposition of radio emission from individual e+ and e-
  - Time-domain calculation
  - Based on "endpoint formalism"

- Superposition of radio emission from individual e+ and e-
  - Time & freq-domain calculation
  - Based on "ZHS algorithm"

- No prior assumptions for "emission mechanisms" – 1st principles.

- Both include realistic refractive index:
  - Treatment of ref. index in curved atmosphere: matters above zenith ~ 80 deg.

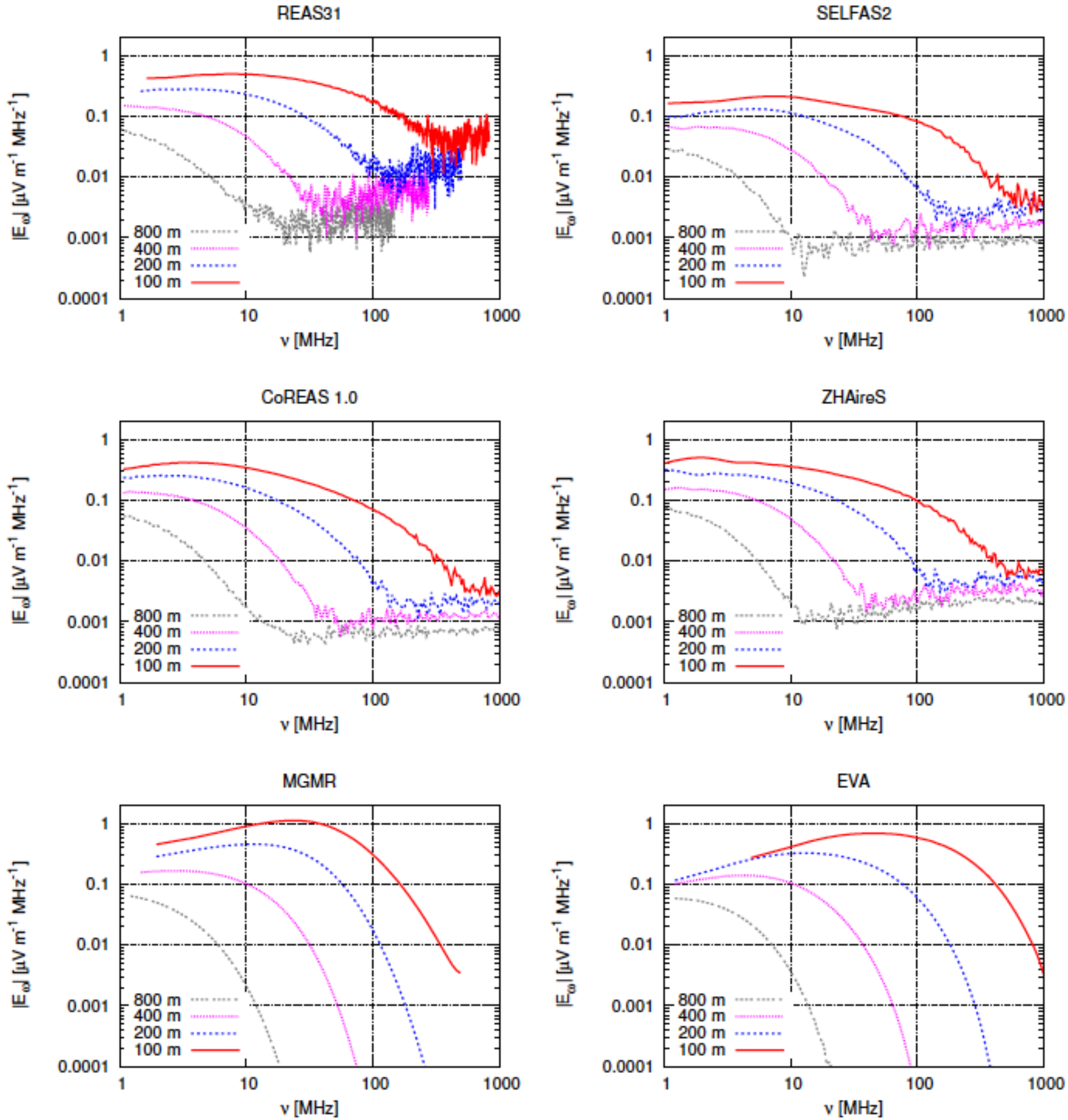
- All features available in underlying shower codes can be used:
  - Different primaries, energies, directions,…
  - ALL hadronic interaction models
  - Different sites on Earth

  - Many hadronic interaction models
  - Also works in dense media
  - Handles reflection of radio emission on Antartcic ice cap

see talk by E. Zas

A few example results of macro & microscopic modeling (air)

Proton
E = 10^{17} eV
θ = 0 deg.
Ref. index n = 1
Pierre Auger site

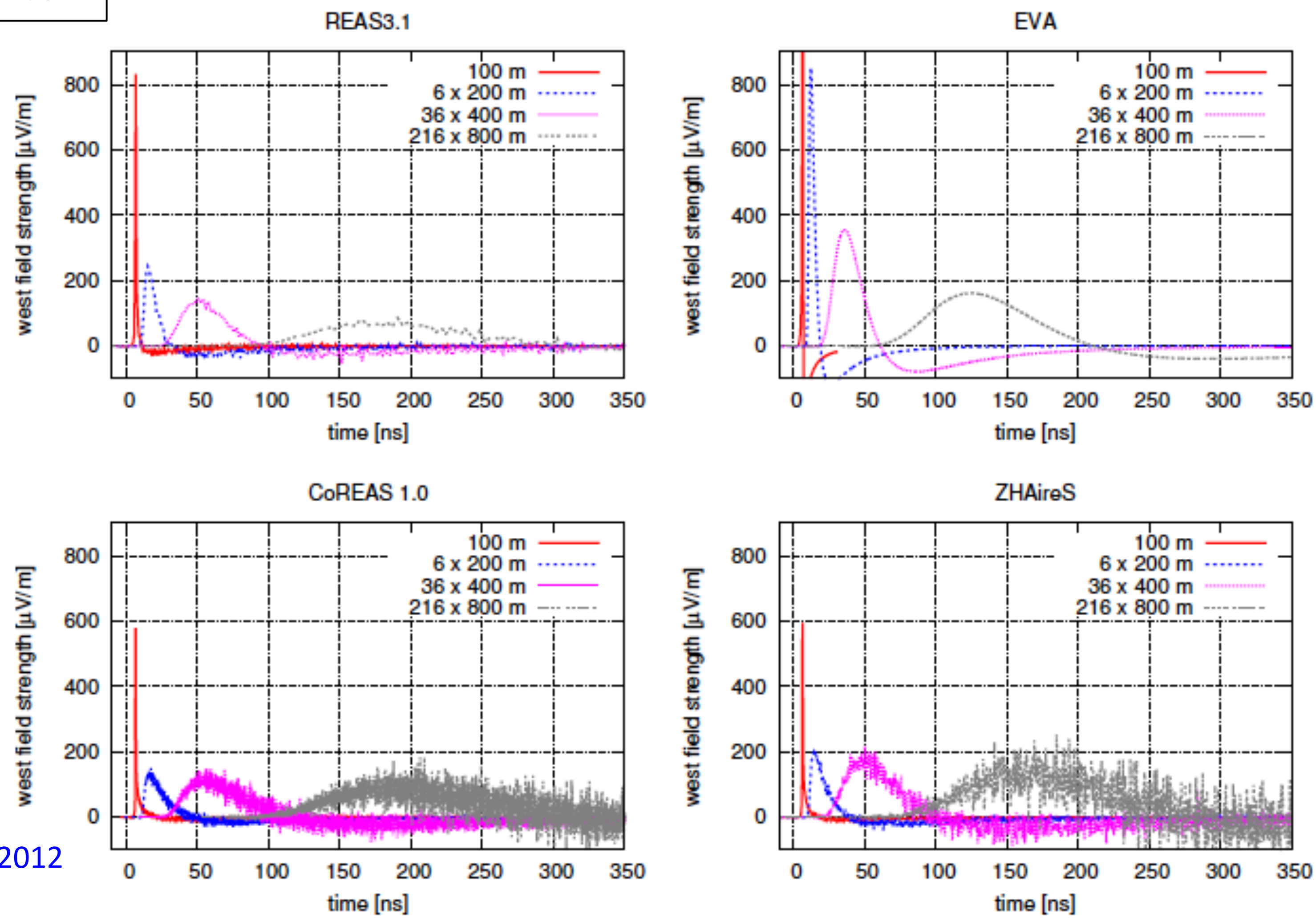


Frequency spectra
(absolute amplitudes)
different distances to
shower core

T. Huege et al.
Ohio Radio Workshop 2012
ARENA 2012

Proton
E = 10^{17} eV
θ = 0 deg.
Realistic n
Pierre Auger site

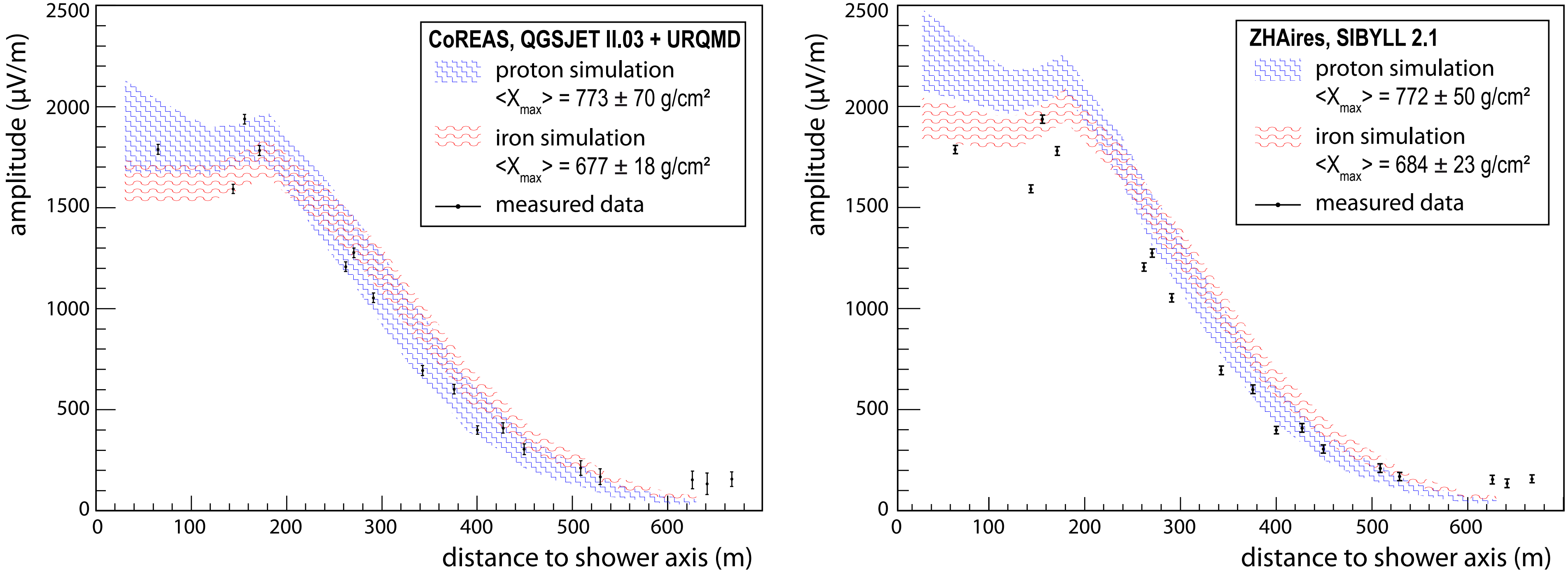
West component of electric field
at different distances to shower core



T. Huege et al.
Ohio Radio Workshop 2012
ARENA 2012

Models & data

AERA data: hybrid (SD & radio) event: E ~ 4 10^{18} eV, θ ~ 58 deg.



F. Schröder (Auger – AERA) ICRC13

Also micro & macro models satisfactoraly compared to:

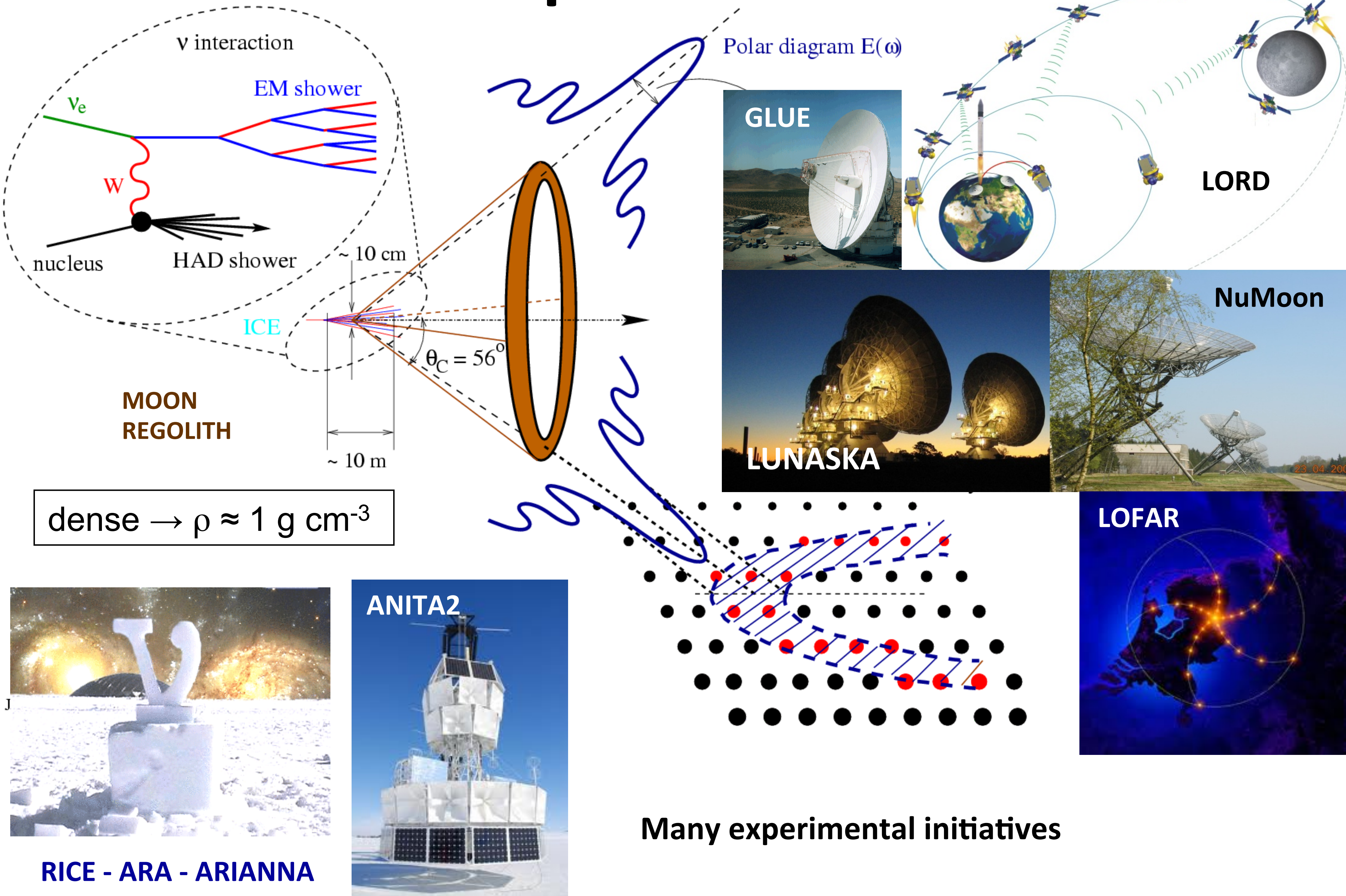
- Auger-AERA polarization data - Pierre Auger Collab. PRD **89**, 052002 (2014)
- LOFAR data - S. Buitink et al.
- SLAC T-510 data – K. Mulrey et al.

Conclusions

- **Good understanding** of radiation mechanisms in dense media and air:
  - Dense media: Askaryan mechanism (radiation).
  - Air: Interference between Askaryan & geomagnetic mechs.
- **Cherenkov-like effects** play crucial role.
- **Macroscopic & Microscopic** modeling:
  - Agreement in many situations: especially in dense media.
  - Complementary: both needed !
- **Benchmark has to be the data:**
  - Several models in good agreement with data (talk T. Huege).

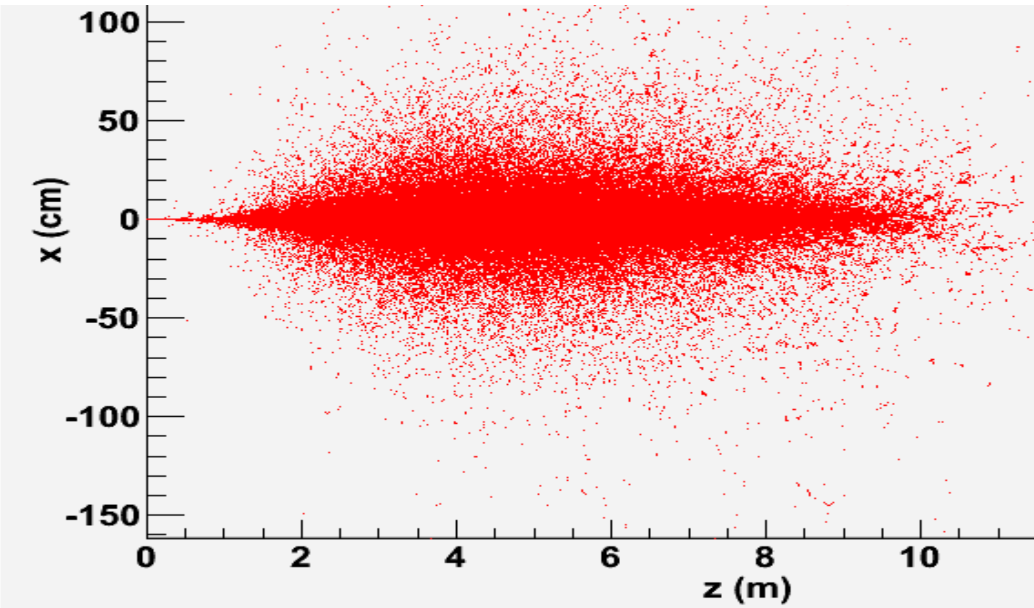
Backup slides

The radio technique in dense media



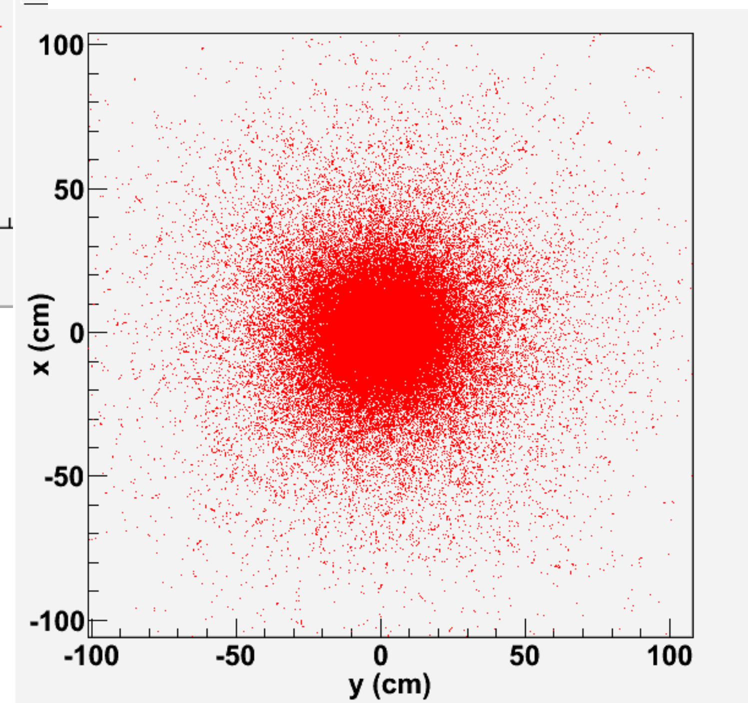
Dimensions & speed of the source

Longitudinal spread
(Radiation length $X_0 \approx 39$ m in ice)



1 TeV electron shower ice

Lateral spread
(Moliere radius $r_M \approx 10$ cm in ice)



Longitudinal spread in ice increases as:

- log E — E < 1 PeV
- $E^{0.3\text{-}0.5}$ — E > 1 PeV can reach ≈ 100 m

Lateral spread varies slowly with E

Ultra-relativistic electrons above K ≈100 keV
v > c/n (n=1.78)

Zas-Halzen-Stanev (ZHS) MC, PRD 45, 362 (1992)

Askaryan effect

G. Askar´yan, Soviet Phys. JETP 14, 441 (1962)

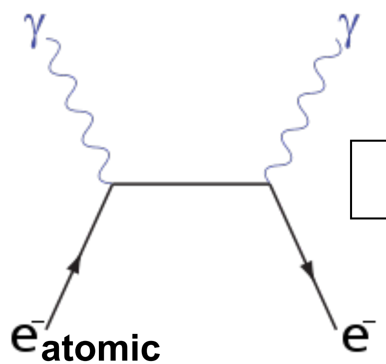
- "Entrainment" of electrons from the medium as shower penetrates

  Excess negative charge develops (electrons) →

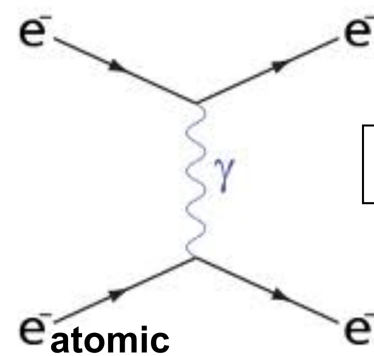
$$\Delta q = \frac{N(e^-) - N(e^+)}{N(e^-) + N(e^+)} \approx 25\%$$

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

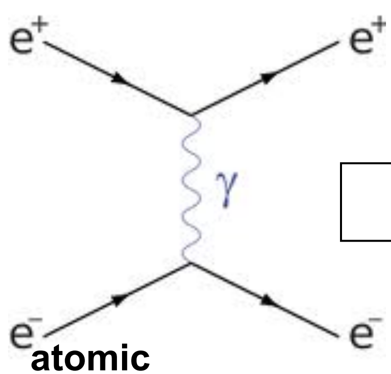
- Main interactions contributing:



Compton



Moeller



Bhabha

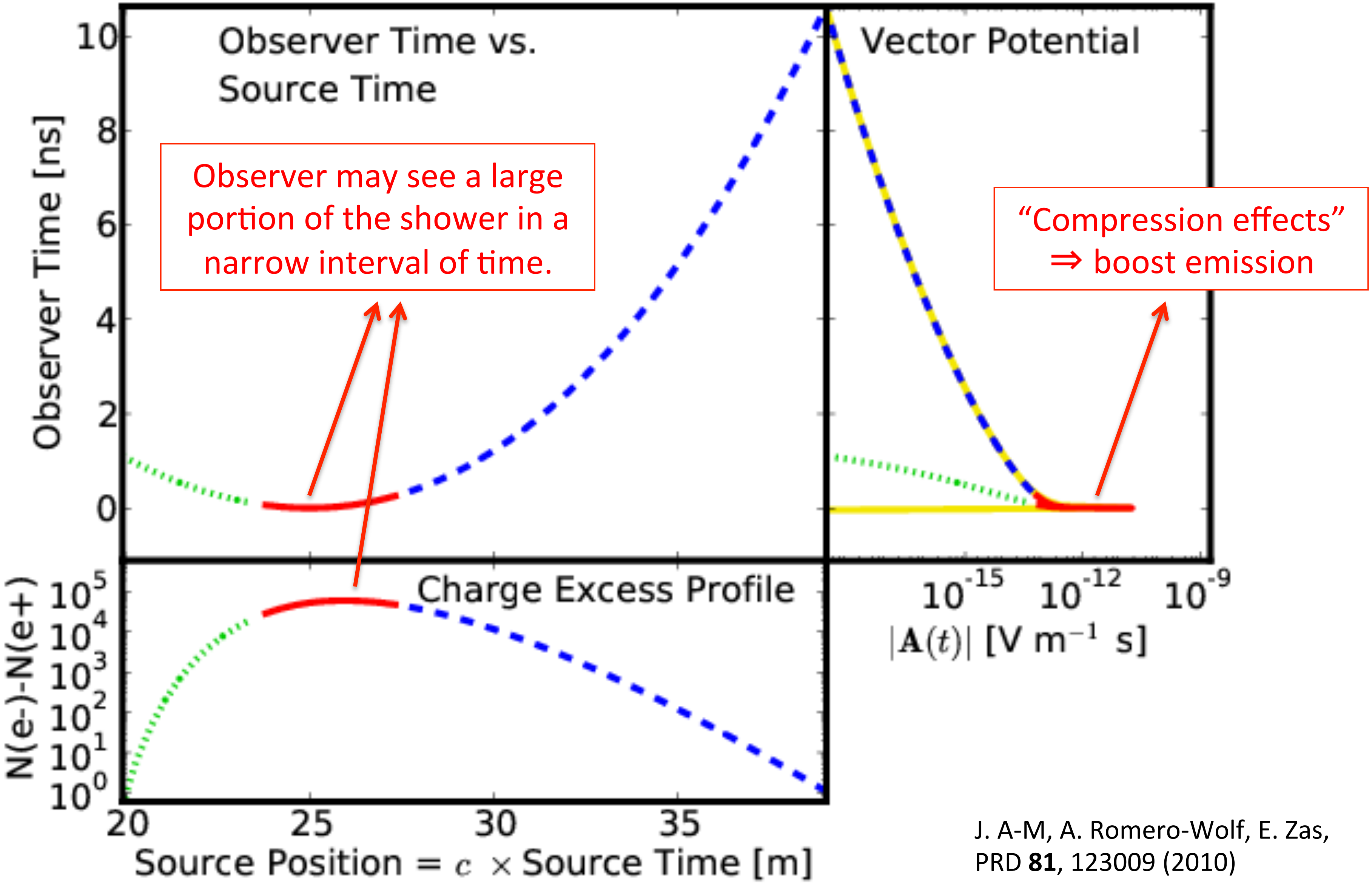
e^+ annhilation

G.A. Askaryan

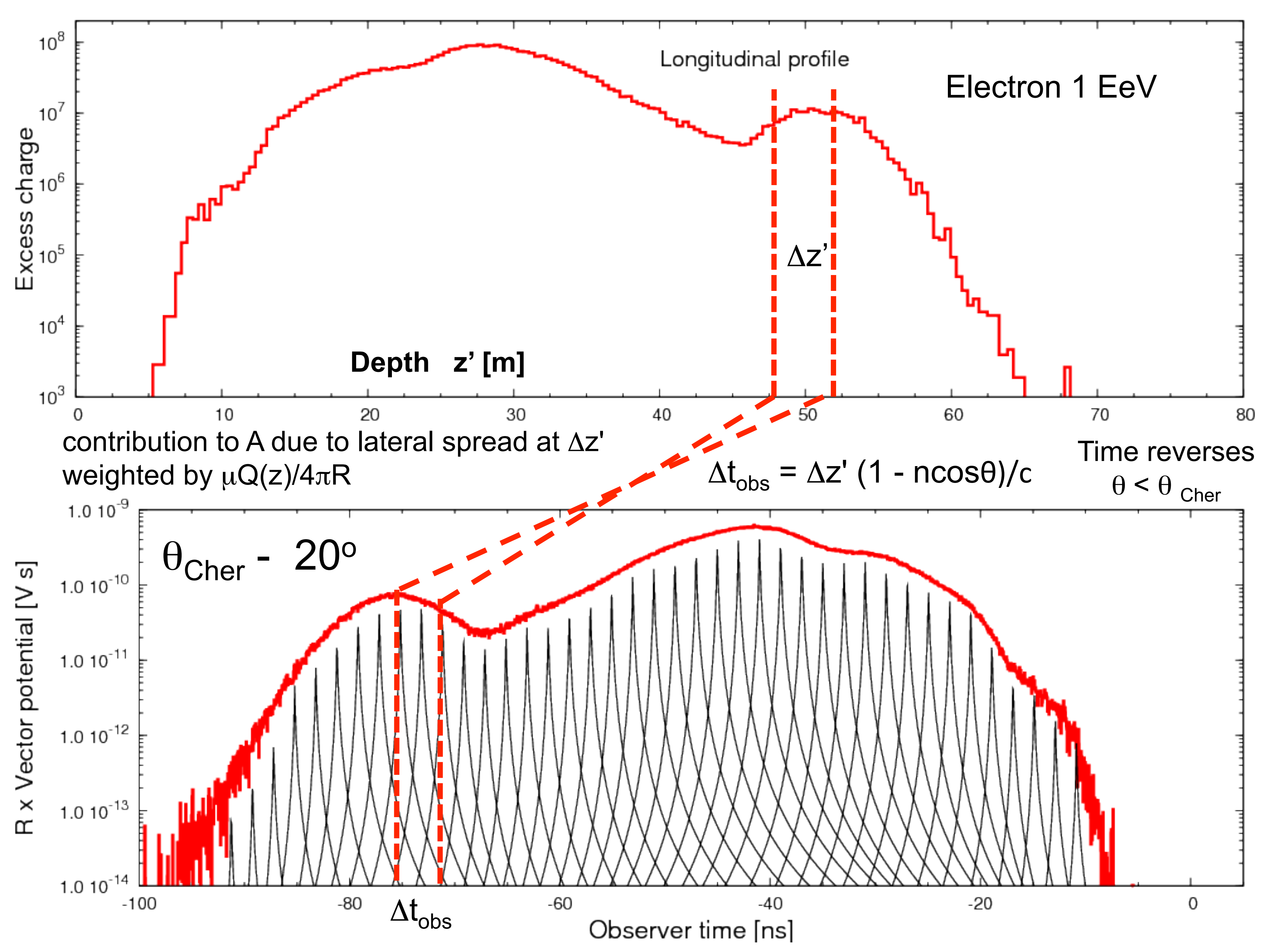
Askaryan effect confirmed in SLAC experiments

Askaryan effect present in any medium with bound electrons (for instance in air).

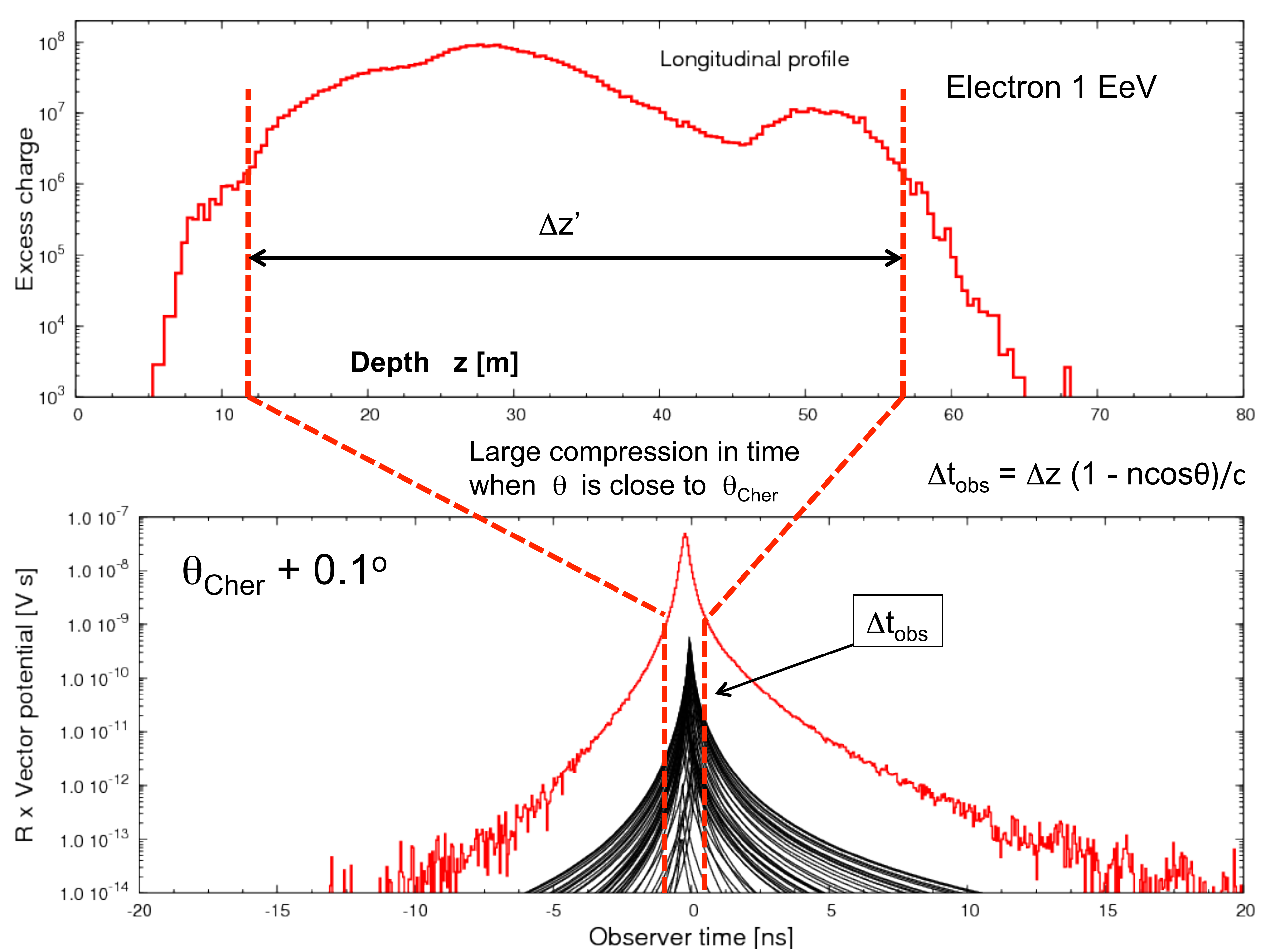
Observer not in the far-field



J. A-M, A. Romero-Wolf, E. Zas, PRD **81**, 123009 (2010)



Longitudinal profile
Electron 1 EeV
Excess charge
Depth z' [m]
Δz'
contribution to A due to lateral spread at Δz'
weighted by μQ(z)/4πR
Δt_obs = Δz' (1 - ncosθ)/c
Time reverses
θ < θ Cher
θ_Cher - 20°
R x Vector potential [V s]
Δt_obs
Observer time [ns]


Longitudinal profile
Electron 1 EeV
Excess charge
Δz'
Depth z [m]
Large compression in time
when θ is close to θCher
Δtobs = Δz (1 - ncosθ)/c
θCher + 0.1°
Δtobs
R x Vector potential [V s]
Observer time [ns]

The Zas-Halzen-Stanev (ZHS) code

ZHS-"multi-media"

- Based on ZHS originally developed in 1993.
- Electromagnetic showers only (E < 100 EeV - thinned)
  - All EM processes included (bremss, pair prod., Moeller, Compton, Bhabha, e+ annhilation, dE/dX,…)
- Multi-media: (Almost) any dense, dielectric & homogeneous medium can be used
  - Ice, sand, salt, Moon regolith,…
- Tracking of particles in small linear steps + ZHS algorithm
- E-field can be calculated in:
  - Time-domain & Frequency-domain.
  - Far-field (Fraunhofer) and near-field (Fresnel).

[J. A-M, C.W. James, R.J. Protheroe, E. Zas , Astropart. Phys. **32**, 100 (2009)]

[J. A-M, A. Romero-Wolf, E. Zas, PRD **81**, 123009 (2010)]

Also GEANT 3.21 & 4

Razzaque et al. PRD **65** , 103002 (2002)

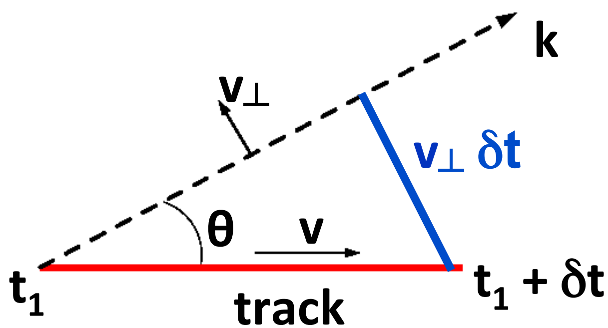
Hussain & McKay PRD **70**, 103003 (2004)

Field single track: frequency domain (ZHS algorithm)

Maxwell´s equations ⇒ Fourier-components of Electric field **E**(ω,**x**) emitted by charged particle traveling along finite straight track at constant speed **v**:

$$\vec{E} \propto \omega \; e \; \frac{\exp(i\,kR\,)}{R} \; \exp[\,i\,(\,\omega - \vec{k}\,\vec{v}\,)\,t_1\,] \; \vec{v}_\perp\,\delta t \; \frac{\sin\varphi}{\varphi}$$

frequency (ω) — global phase ($\frac{\exp(ikR)}{R}$) — phase factor ($\exp[i(\omega - \vec{k}\vec{v})t_1]$) — polarized radiation, tracklength ($\vec{v}_\perp \delta t$) — diffraction ($\frac{\sin\varphi}{\varphi}$)



$$\varphi = \omega\,\delta t\,(\,1 - n\,\beta\,\cos\theta\,)$$

E. Zas, F. Halzen, T. Stanev PRD **45**, 362 (1992)

1. Finite limit at Cherenkov angle.
2. Valid approximations as long as kR >> 1 (k = wavenumber, R = distance to observer)
3. Existing algorithm also in time-domain: J. A-M, A. Romero-Wolf, E. Zas, PRD **81**, 123009 (2010)

Radiation from a shower: frequency domain

Contributions to E-field from all charged particles tracks

Phase factors (different for each particle)

$$E \propto \sum_{\substack{\text{charged}\\ \text{particles}}} E_i \propto \omega \sum e_i \; v_{i\perp} \delta t_i \; \exp[\, i\omega\,(1 - n\,\beta_i \cos\theta\,)\, t_{1i}\,] \; \frac{\sin \varphi_i}{\varphi_i}$$

Charge of each particle

$$\varphi_i = \omega\, \delta t_i \,(1 - n\,\beta_i \cos\theta\,)$$

If $\theta \approx \theta_C$ **or** λ_{obs} >> shower dimensions (small enough ω) at θ

→ Phase factors ≈ equally small → COHERENCE (@ MHz-GHz)

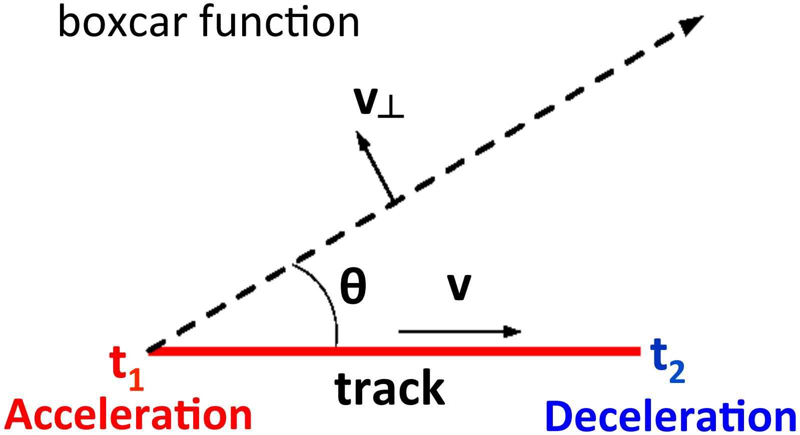
$$\mathbf{E} \approx \omega\, \Sigma\,(-e)\, \mathbf{v}_i\, \delta t_i + \omega\, \Sigma\,(+e)\, \mathbf{v}_i\, \delta t_i \approx \omega\, \Sigma\,(-e)\, \mathbf{v}_i\, \delta t_i$$

electrons **positrons** **charge excess**

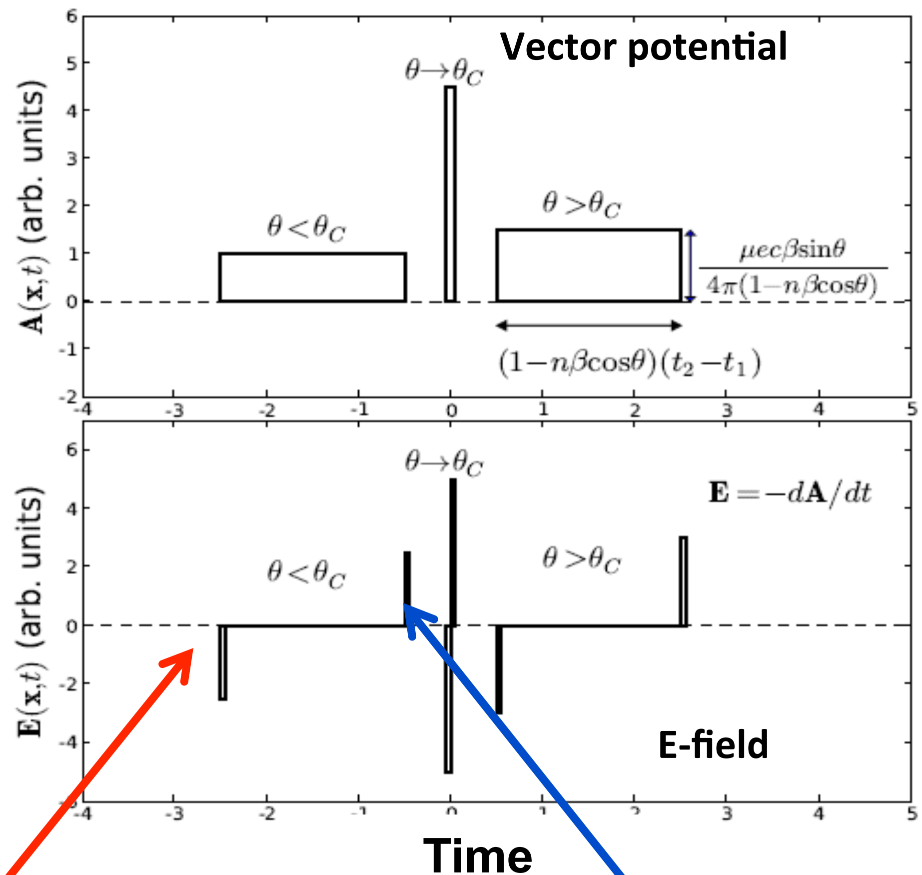
Field single track: Time domain (ARZ algorithm)

Maxwell´s equations → Radiation comes from instantaneous acceleration at start & deceleration at end of particle track

Current modeled as a boxcar function



J. A-M, A. Romero-Wolf, E. Zas, PRD **81**, 123009 (2010)



The "ARZ algorithm"

Acceleration — Deceleration

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

ARZ algorithm can be obtained Fourier-transforming the ZHS algorithm

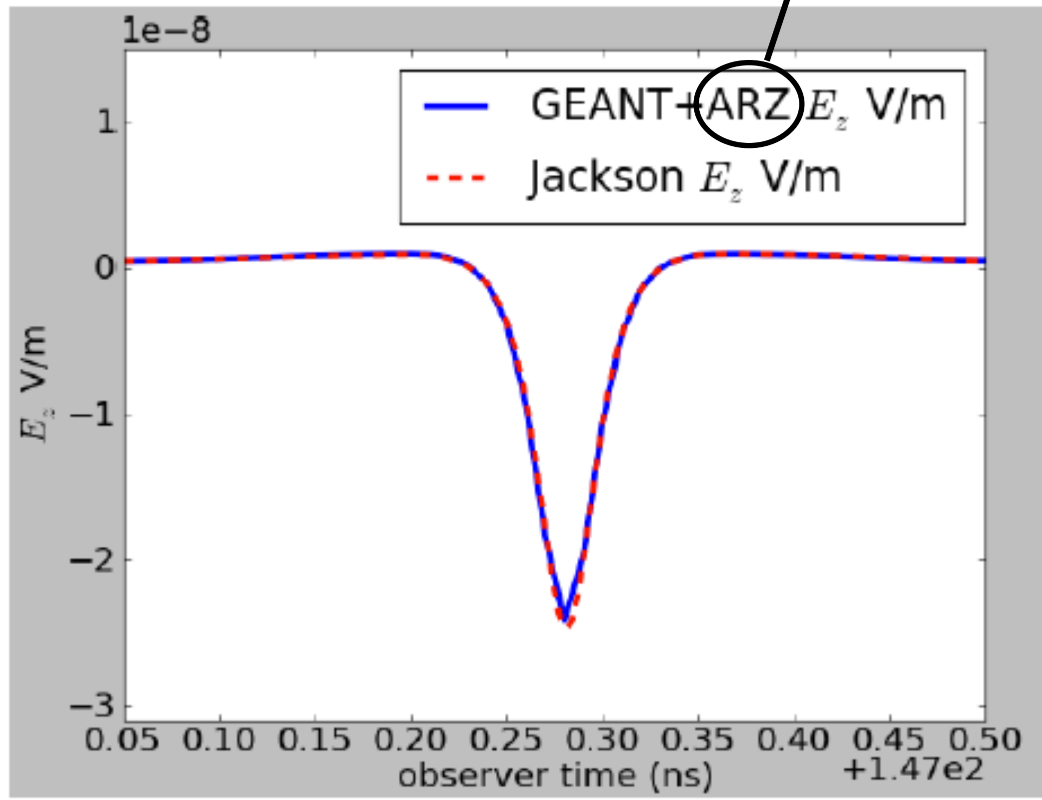
Comparison ZHS algorithm & Jackson

A-M, Romero-Wolf, Zas, PRD **81**, 123009 (2010)]

Compare results from previous slides to the analytical result for circular motion using formula (14.14) of Jackson's Electrodynamics 3rd edition.

$$\vec{E}(\vec{x},t) = \frac{e}{4\pi\varepsilon_0 c}\left[\frac{\hat{n}\times\left[\left(\hat{n}-\vec{\beta}\right)\times\dot{\vec{\beta}}\right]}{\left(1-\vec{\beta}\cdot\hat{n}\right)^3 R}\right]_{ret}$$

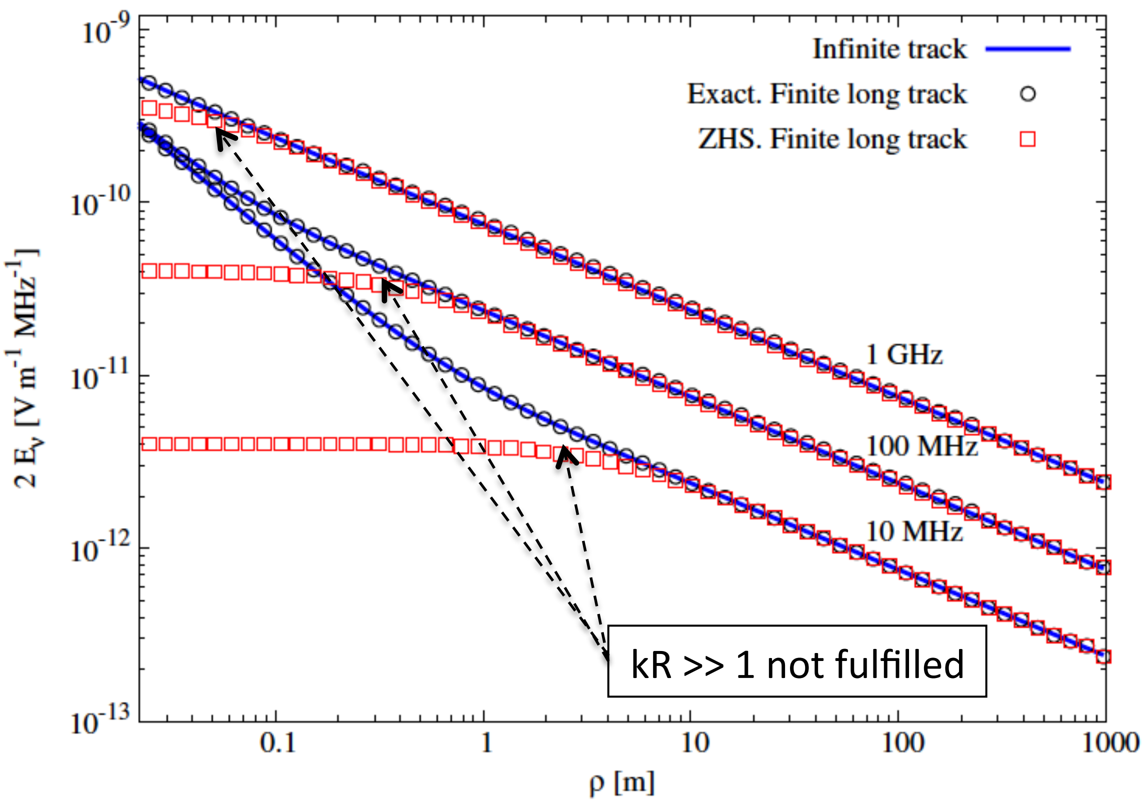
This shows that the ARZ calculation using the vector potential from tracks reproduces the analytical result with high fidelity.



A. Romero-Wolf & K.Belov
(Proposal to test geosynchrotron in SLAC)

ZHS algorithm describes Cherenkov radiation: the case of an infinite track

Infinite track at constant speed => the only radiation is Cherenkov



<u>Behavior with distance of field emitted at various frequencies by:</u>

Infinite track = Analytical calculation of Cherenkov radiation (Afanasiev)

Exact finite long track = result of EXACT field calculation for a very long track (1.2 km).

ZHS Finite long track = result of ZHS algorithm for a very long track (1.2 km)

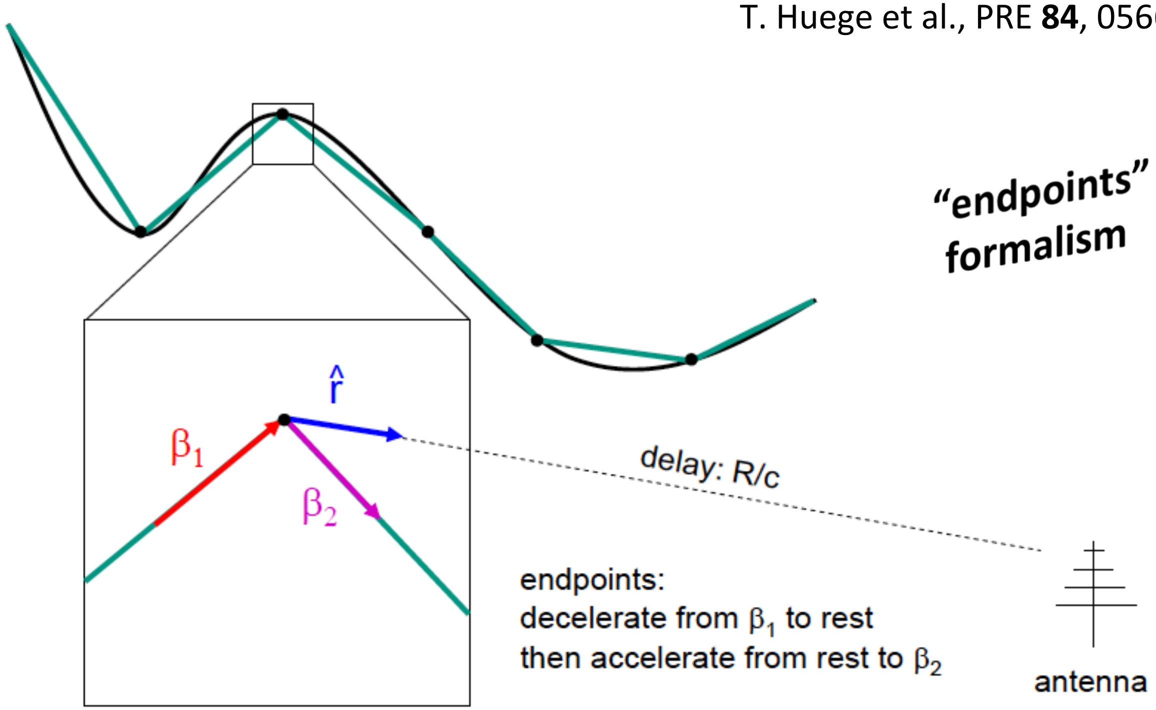
Better than 1% agreement between the 3 calculations as long as observer is in far-field zone:

$$kR \sim 3.7\left(\frac{\nu}{100\ \mathrm{MHz}}\right)\left(\frac{R}{1\ \mathrm{m}}\right) \gg 1.$$

D. García-Fernández, et al. PRD **87**, 023003 (2013)

Field single track: frequency domain (endpoints algorithm)

T. Huege et al., PRE **84**, 056602 (2011)

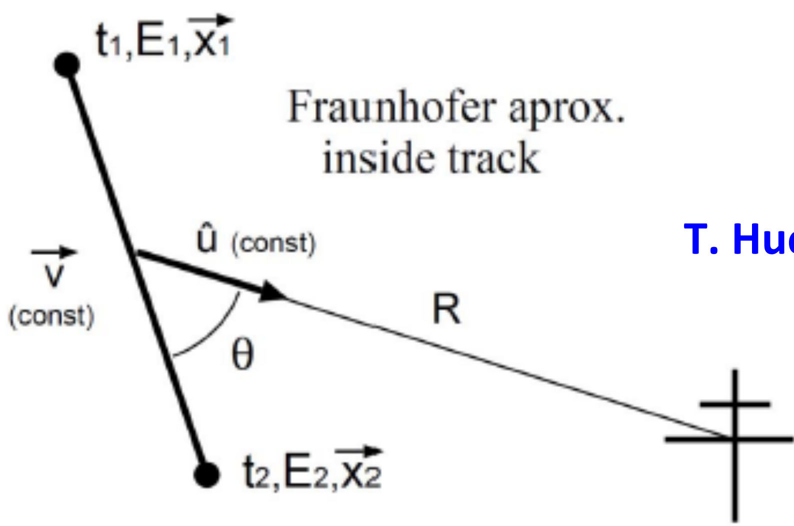


Frequency-domain
$$\vec{E}_{\pm}(\vec{x},\nu) = \pm\frac{q}{c}\,\frac{e^{ikR(t_0')}}{R(t_0')}\,\frac{e^{2\pi i\nu t_0'}}{1-n\vec{\beta}^*\cdot\hat{r}}\,\hat{r}\times[\hat{r}\times\vec{\beta}^*]$$

1. Radiation only from endpoints: acceleration & deceleration events along particle trajectory
2. Breaks down at Cherenkov angle => adopts ZHS treatment
3. Existing algorithm also in time-domain

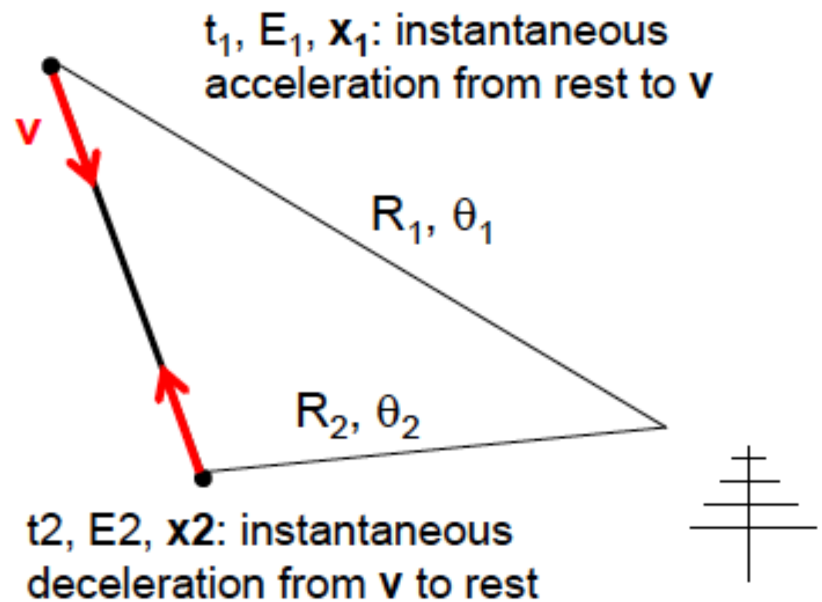
ZHS algorithm vs endpoints

- sum up vector potentials, do time-derivative at the end



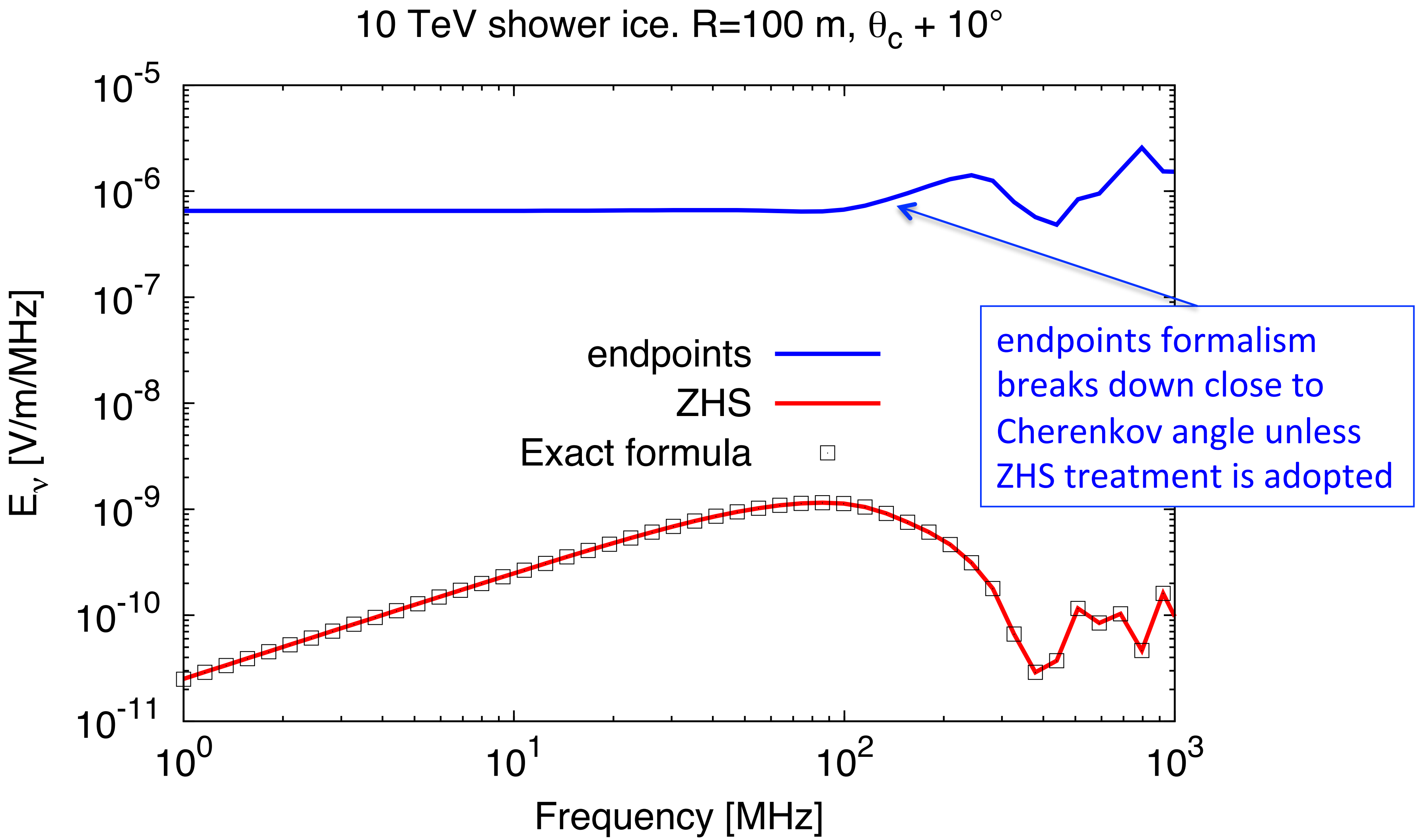
T. Huege

- do time-derivative at start, sum up electric fields

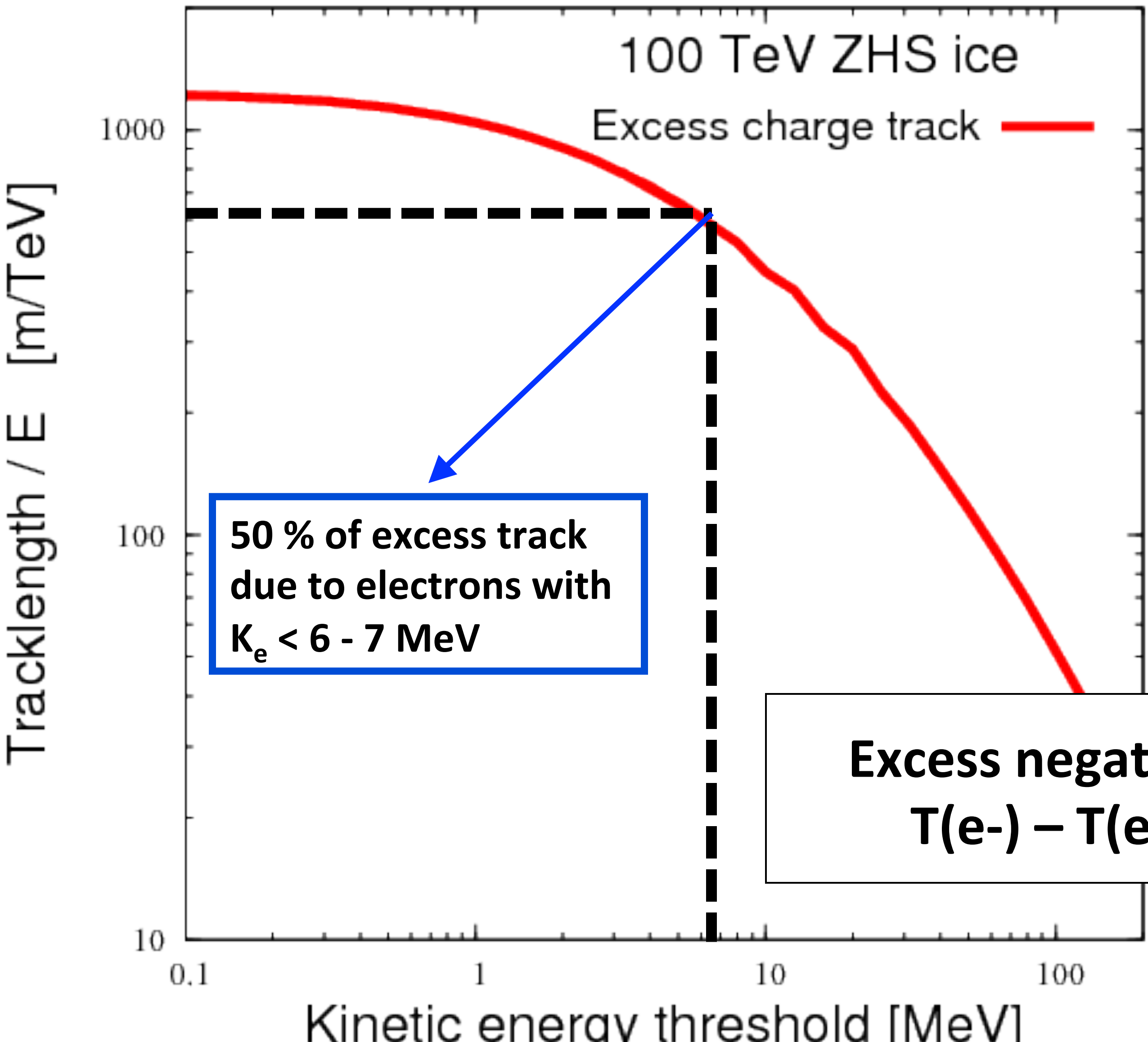


- Both equivalent in the far-field & at angles away from the Cherenkov angle
- endpoints reverts to ZHS close to Cherenkov angle to avoid singularities
- ZHS limit close to Cherenkov angle validated with exact calculation (see previous slides)
- SLAC T510 experiment (talk at this meeting) will test these algorithms.

ZHS vs exact calculation vs (pure) endpoints



Modeling with MC: "Low" energies matter…



keV-MeV electrons contribute most to radio emission

Excess negative tracklength:
T(e-) – T(e+) vs $K_{threshold}$

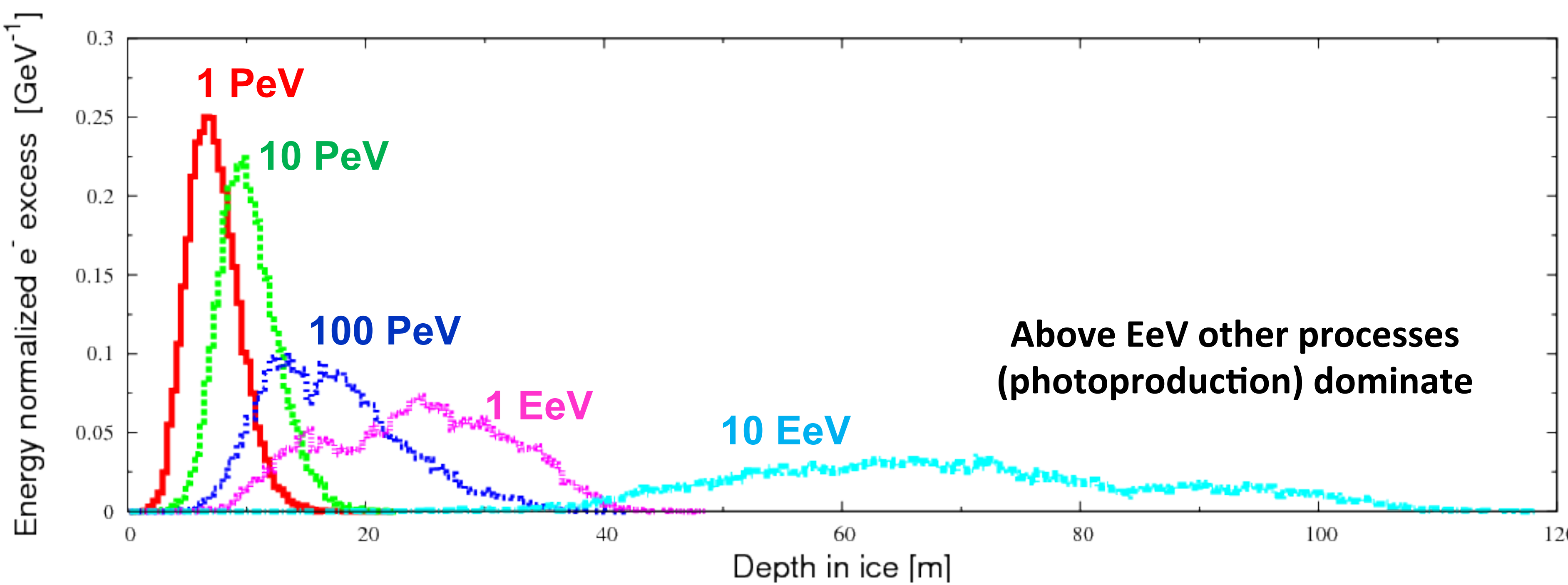
E. Zas, F. Halzen, T. Stanev PRD **45**, 362 (1992)

LPM effect in EM showers

Screening effect on electron & photon interaction reduces bremsstrahlung & pair-production cross sections w.r.t. Bethe-Heitler predictions

Electromagnetic showers having $E > E_{LPM}$ (~ 2 PeV in ice – medium dependant):

- Long. dimension **L** increases faster than ~ log E, typically as E^{β}, $\beta \sim ⅓ – ½$
  Produces multiple lumps in long. development at highest energies.
- Lateral dimension R does not change much with shower energy.



Askaryan radiation
Time-domain
LPM showers

Vector potential traces shape of longitudinal profile: maxima -> zero-crossings

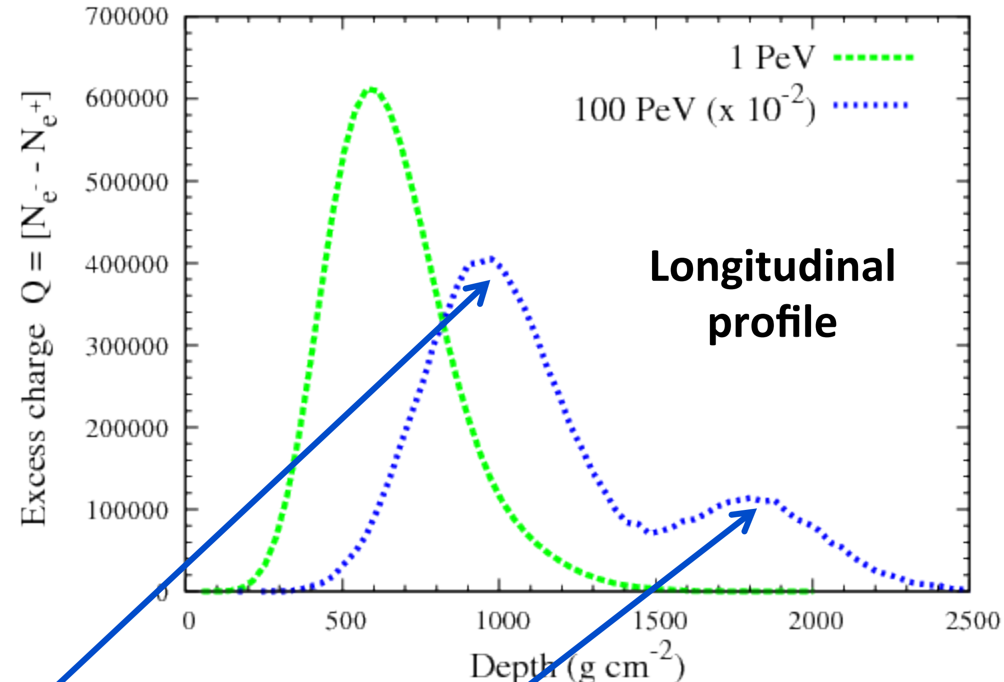
E-field *(derivative of vector potential)* exhibits multiple peaks in LPM showers.

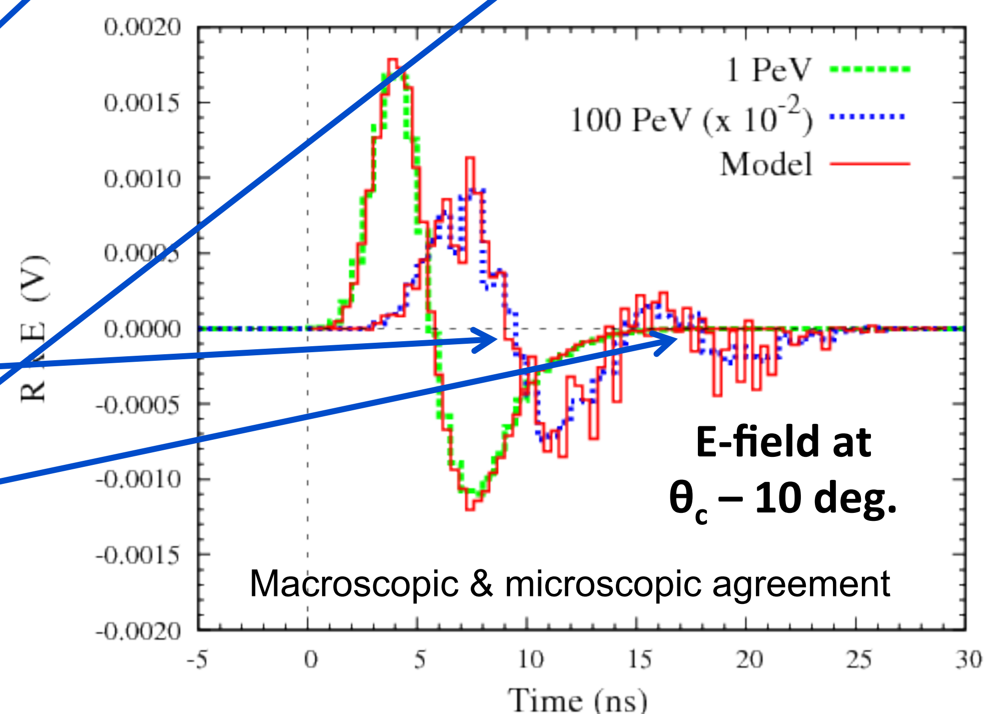
… as expected.

1st peak:
1st zero

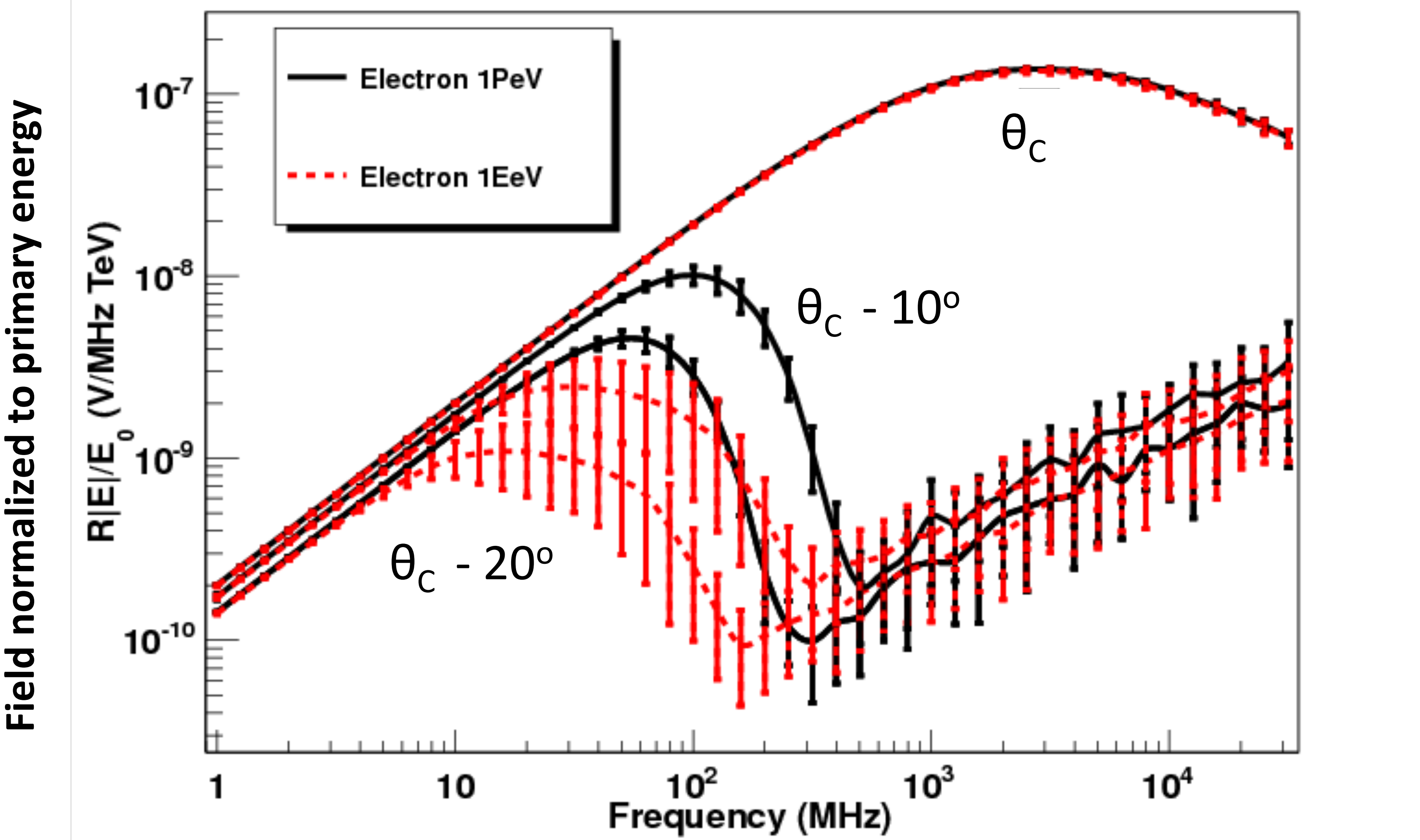
2nd peak
2nd zero

(Far-field observers)





Frequency spectrum in "LPM showers"



- Elongated profiles at EeV induce smaller cut-off frequencies at $\theta \neq \theta_c$
- Cut-off frequency at Cherenkov angle unaffected.
- Large shower-to-shower fluctuations

Hadronic showers

Primary proton, nucleus, jet in neutrino interaction.

Hadronic core (penetrating) continually **feeding EM component** through $\pi^0 \longrightarrow \gamma\,\gamma$

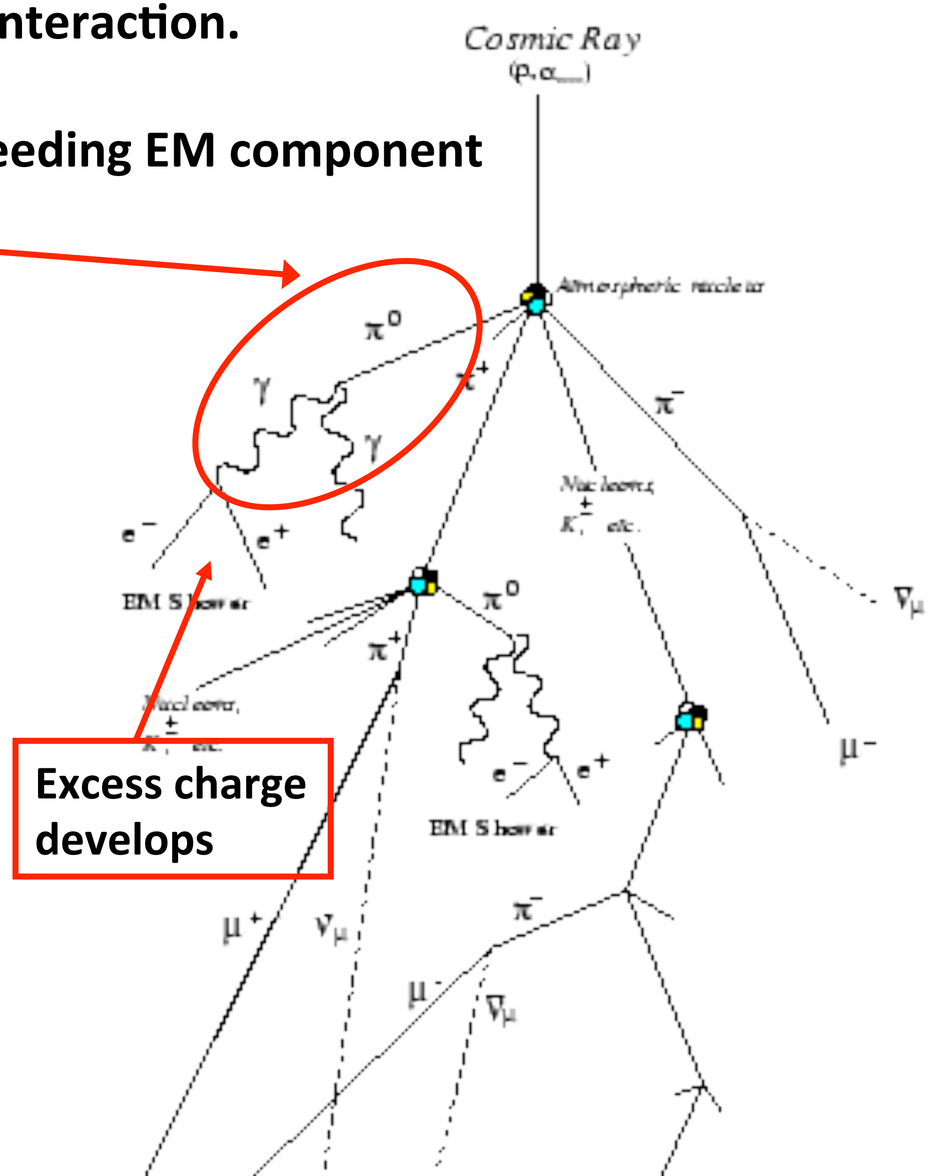
Markedly electromag. character:
% of primary energy into EM component

$\approx$ 69% at 1 TeV
$\approx$ 89% at 1 PeV
$\approx$ 93% at 1 EeV

Showers emit radiation more efficiently as energy increases.

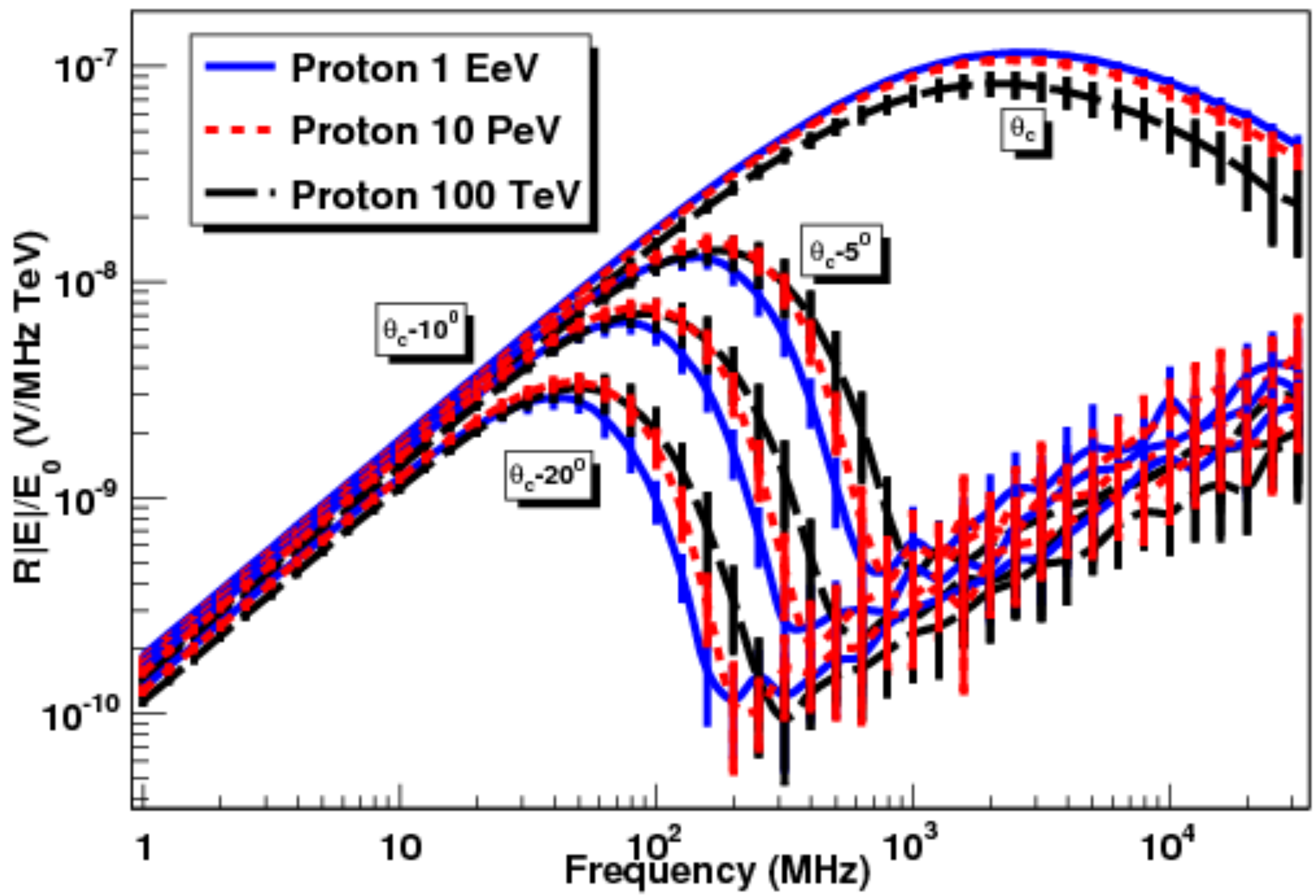
LPM less effective: Weakened effects of shower elongation with energy.

Lateral spread decreases slowly with shower energy.



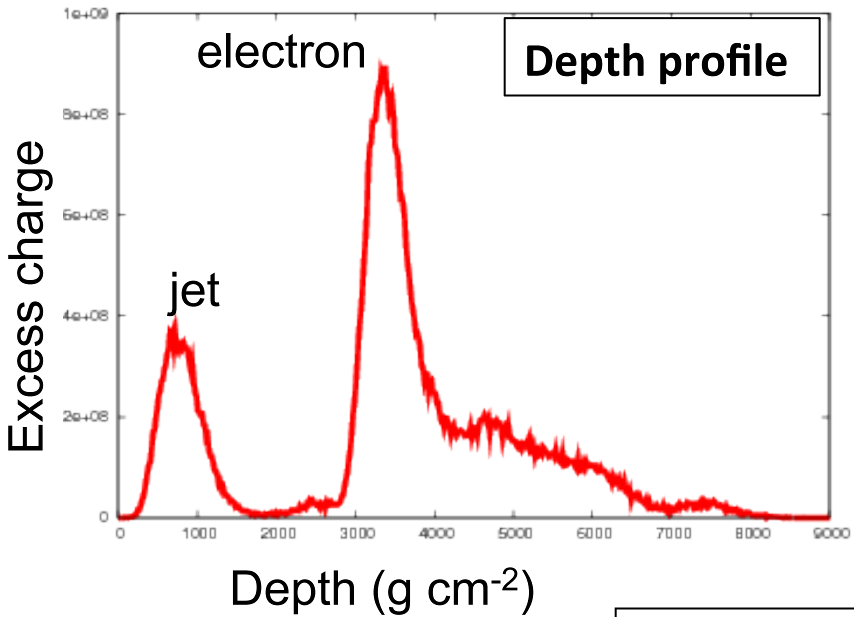
Freq. spectrum – Hadronic showers

- Slow elongation with energy → small cut-off frequencies at $\theta \neq \theta_c$
- Cut-off frequency at Cherenkov angle increases slowly with energy



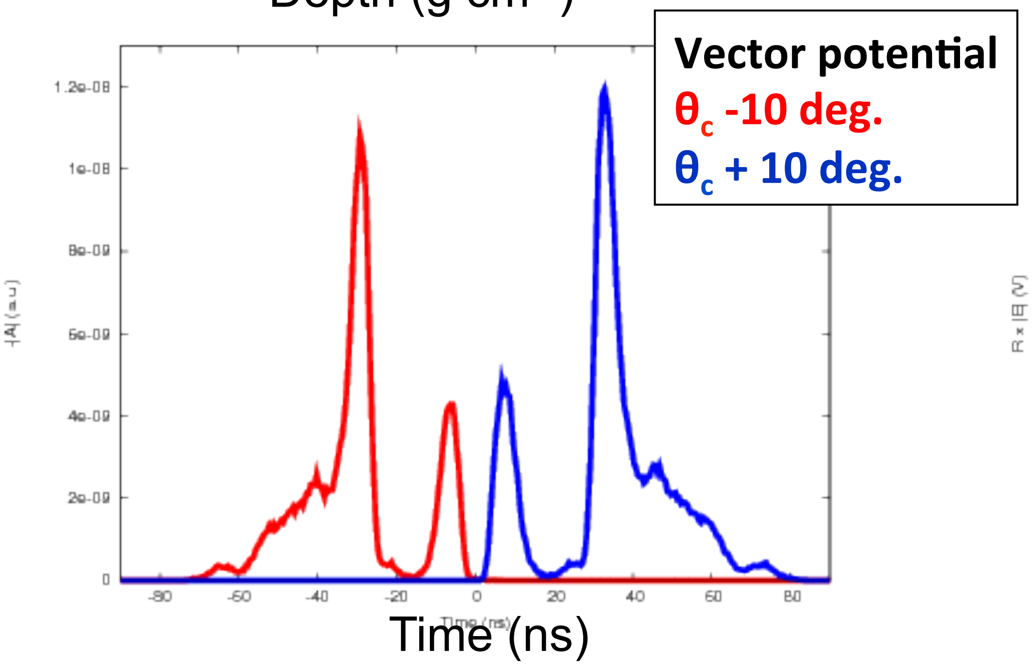
Contribution to radio-emission from:
protons + charged pions + muons + charged kaons **< 2%** above PeV

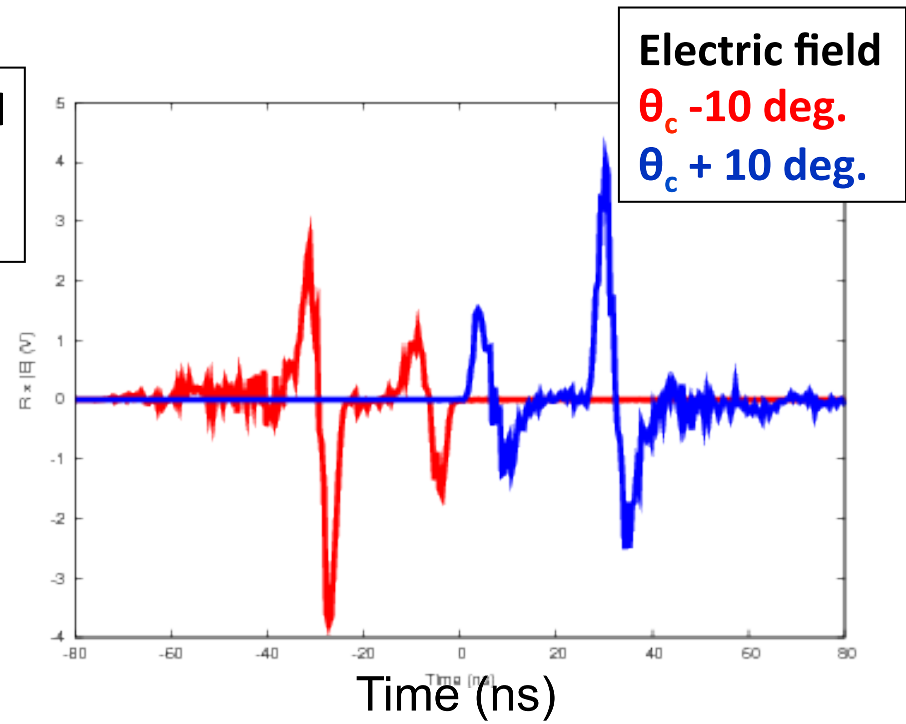
Time-pulses in ν-induced showers



$$\nu_e + N \longrightarrow e + jet$$

$E(\nu_e)$ = 10 EeV
E(electron) = 8 EeV
E(hadronic jet) = 2 EeV



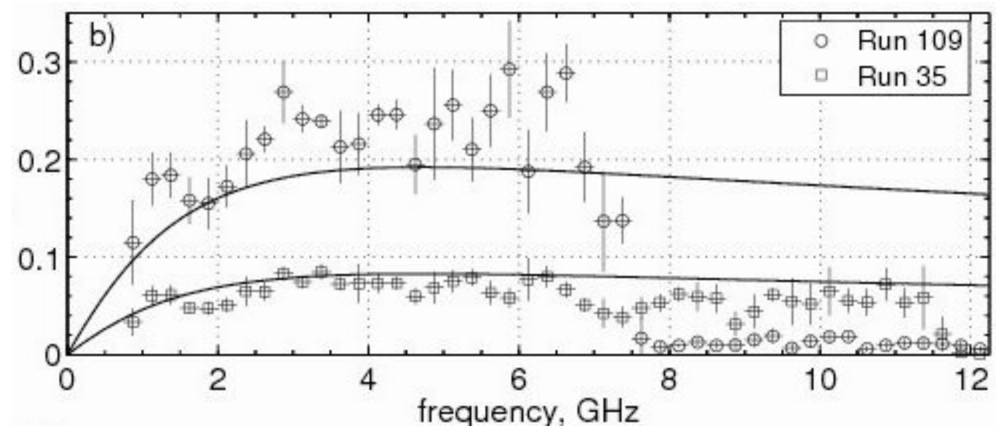


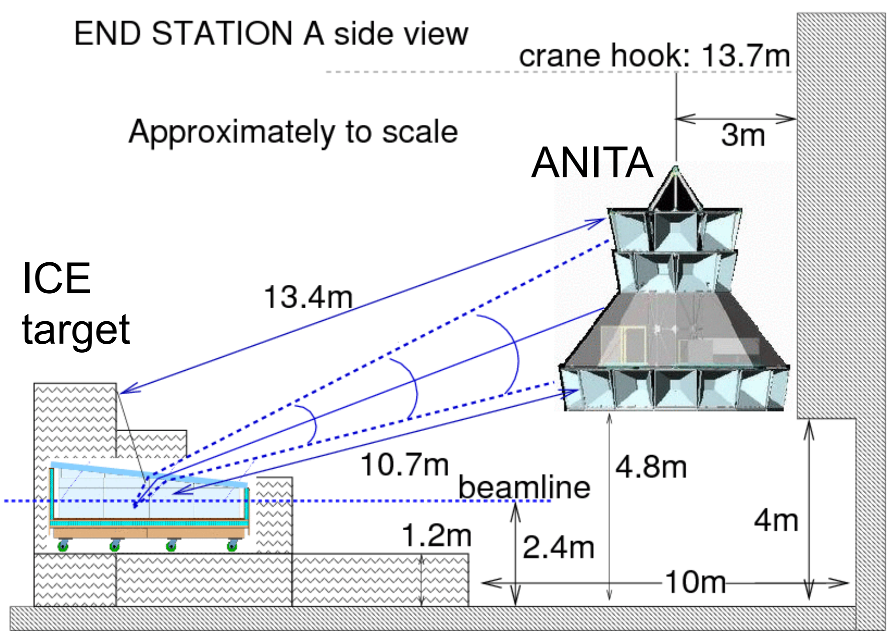
Experiments at SLAC: sand, salt & ice

Bunches of ~ GeV bremss. photons dumped in sand & salt & ice: $E_0 \sim 6 \times 10^{17} - 10^{19}$ eV .

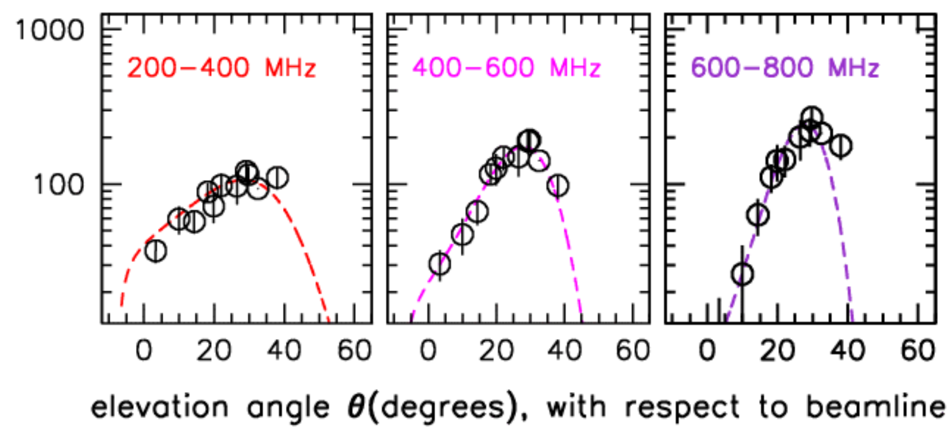
- Askaryan effect seen !!!
- Linearly polarized signal
- Power in radio waves goes as E_0^2
- Bipolar pulses in time-domain
- Agreement with theoretical expectations

Frequency spectrum





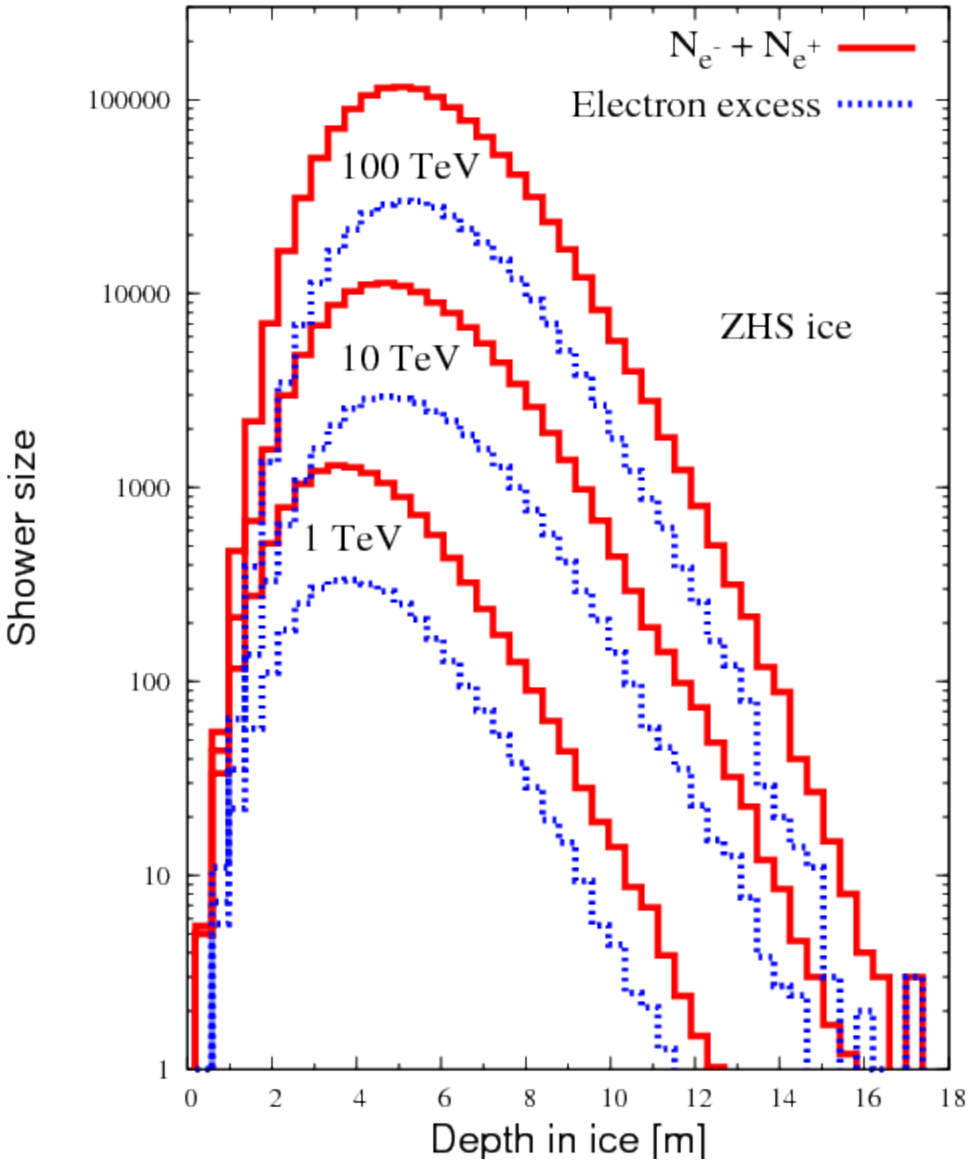
Angular distribution of electric field



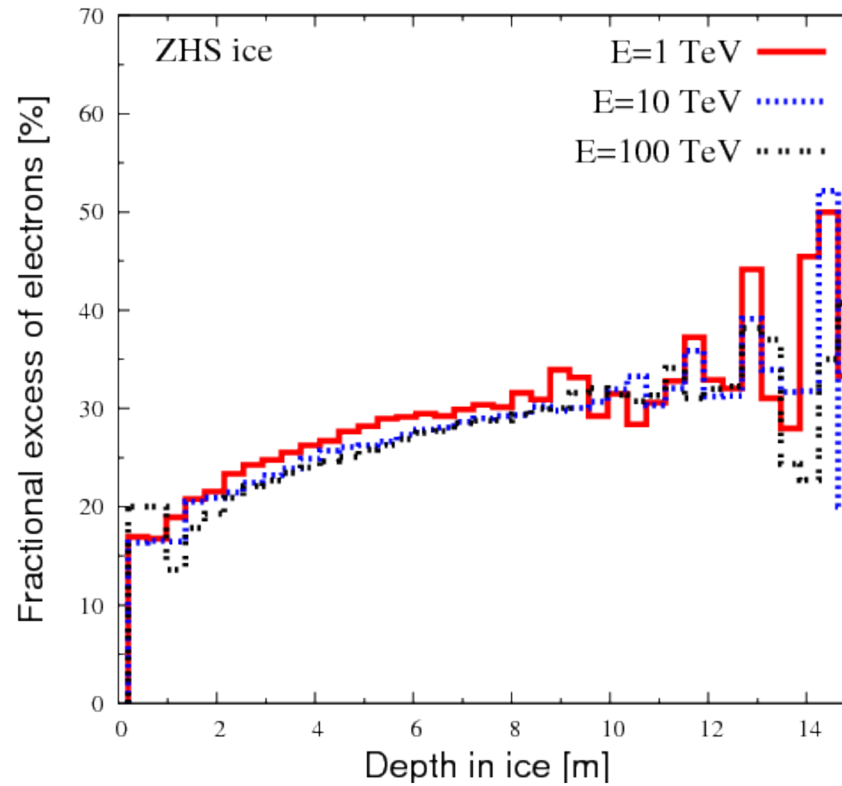
D. Saltzberg et al. PRL **86** (2001); P.Miocinovic et al. PRD **74** (2006), P. Gorham et al. PRL **9**9 (2007)

Excess negative charge

$$\Delta q = \frac{N(e^-) - N(e^+)}{N(e^-) + N(e^+)} \approx 25\%$$



ZHS Monte Carlo simulations e-induced showers in ice

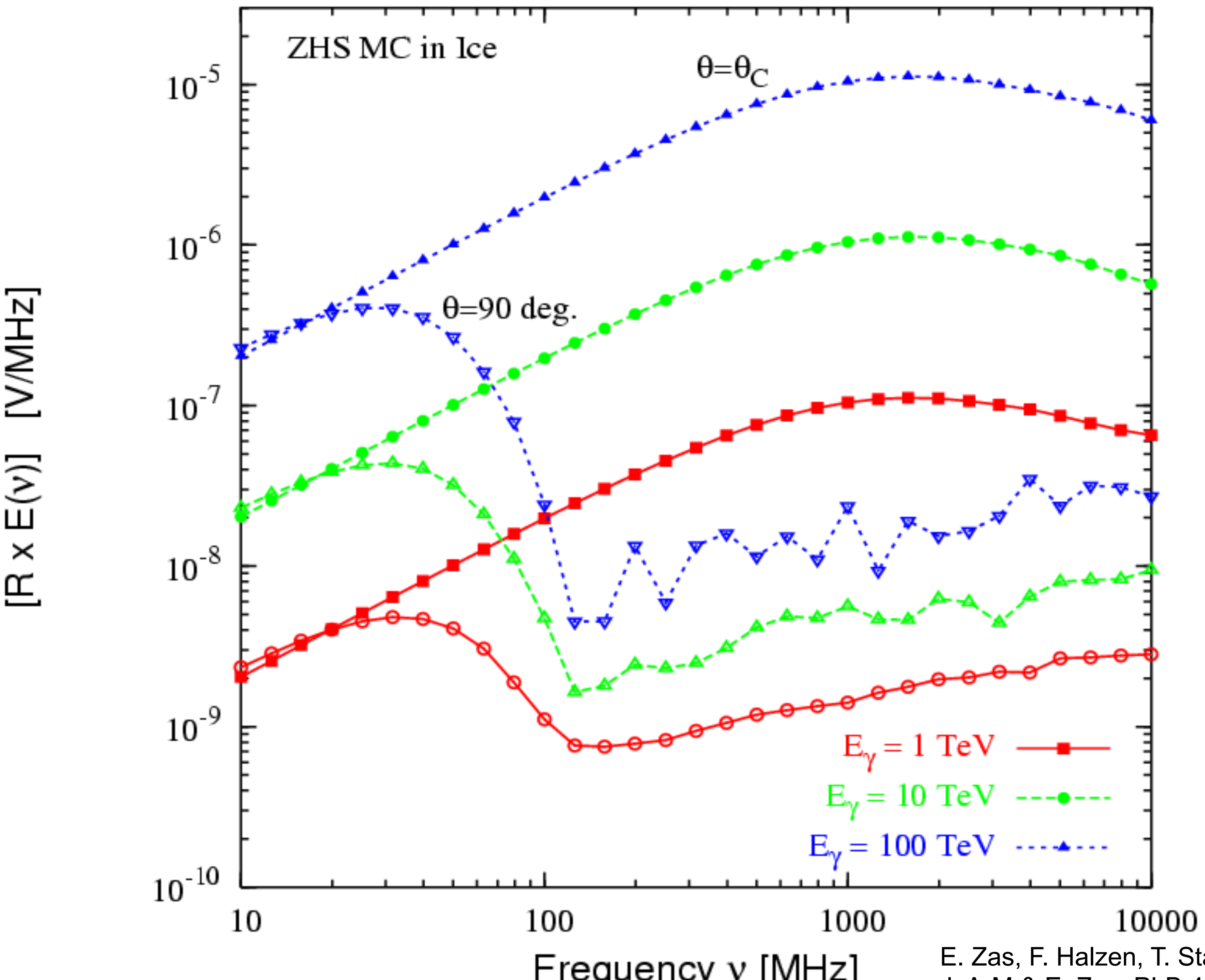


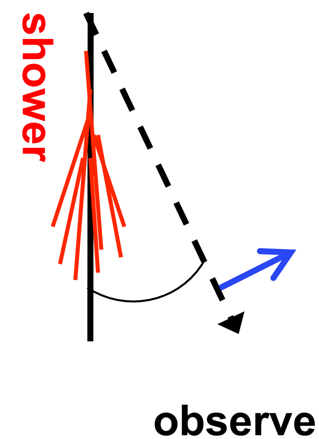
Δq scales with shower E.

Δq increases slowly with depth.

Δq depends on medium.

Frequency spectrum – EM showers





E. Zas, F. Halzen, T. Stanev, PRD 45, 162 (1992),
J. A-M & E. Zas, PLB 411, 218 (1997)

Conclusions from "box" model

- **Far-field observer at Cherenkov angle (θ_c):**
  - Spread in time of pulses and frequency cut-off determined by lateral spread of shower (R).

- **Far-field observer at $\theta \neq \theta_c$:**
  - Spread in time of pulses and frequency cut-off (mainly) determined by longitudinal spread of shower (L).

Conclusion from 1D line model

- Modelling signal away from Cherenkov simple & straightforward
  - Time-domain: vector potential = rescaling & time-transforming longitudinal profile.
  - Freq.-domain: Electric field = Fourier transform of longitudinal profile.

(Longitudinal profile easy/fast to obtain with MC simulations)

Conclusion from 3D model

- Modelling signal at any θ is simple & straightforward
  - Vector potential = convolution longitudinal & lateral contributions, with appropriate rescaling & time-compression.
  - Lateral contribution = form factor (easily obtained in MC sims. from vector potential at Cherenkov angle)
  - Longitudinal profile modeled with MC sims. (fast !)
- Procedure works in the far-field & "near"-field

  (near-field = distances > lateral shower dimensions i.e. > 1 m)
- Procedure works also for p, ν showers
  - Simply use lateral contribution corresponding to hadronic showers or a mixture in case of ν_e Charged Current

Parameterisations of radio signals

Karlsruhe Institute of Technology

- CoREAS parametrization and online calculator for AERA
  - GAP2013-084 (A. Huber, T. Huege)
  - calculator at: http://www-ik.fzk.de/~huege/coreasparam.html
- CoREAS parametrization for Europe (LOFAR) location
  - arXiv:1402.2872 (A. Nelles et al.)
- method to calculate complete asymmetric radio LDF from ZHAireS simulations along one observer azimuth direction
  - arXiv:1402.3504 (J. Alvarez-Muniz et al.)