Phenomenology of transition radiation at radio frequencies from ultrahigh-energy showers

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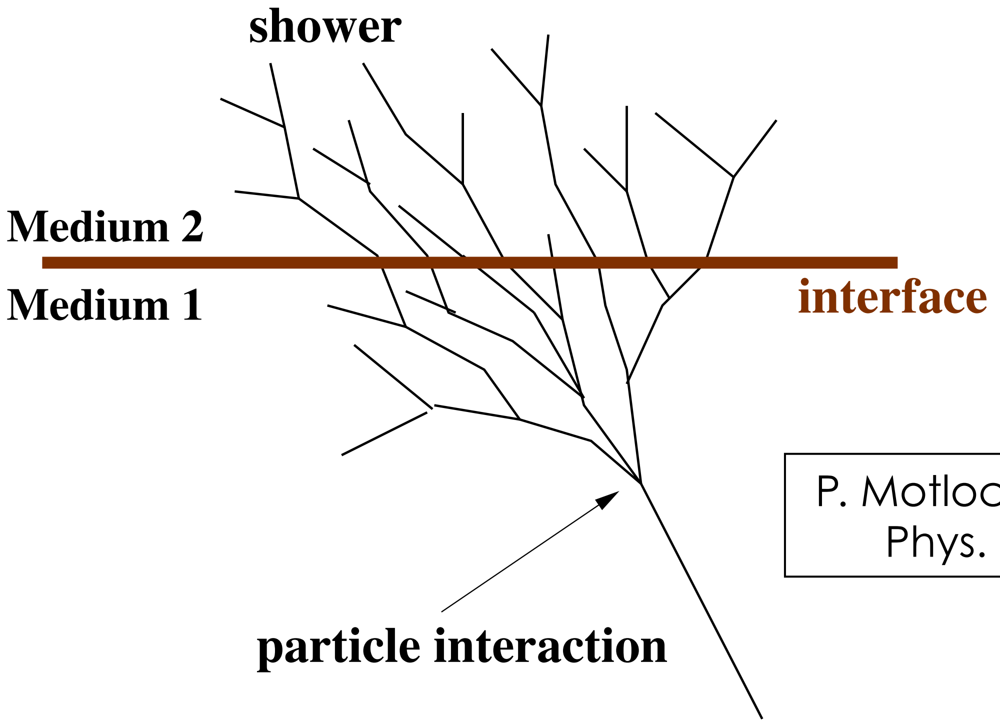
Aim

- **Characterize properties** of radiation (MHz-GHz) emitted in particle showers crossing interface between two dielectric media:
  - from dense media to air (or vacuum)
  - from air to dense media*
- Study **pros & cons of Transition Radiation** as detection technique for UHE neutrinos



P. Motloch, J.A-M, P. Privitera, E. Zas
Phys. Rev. D **93**, 04310 (2016)

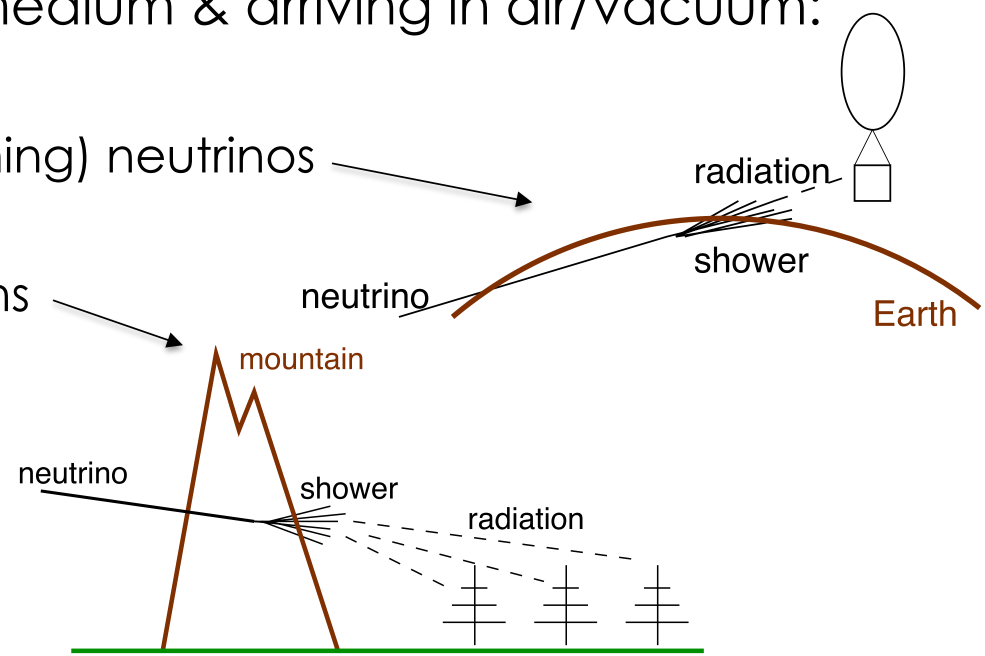
* see also K. de Vries et al. Astropart. Phys. **74**, 96 (2016)

Motivation

There are several situations where showers crossing a boundary might be useful for detection of UHECR and/or ν:

A. Showers starting in dense medium & arriving in air/vacuum:

- Upward-going (Earth-skimming) neutrinos
- Neutrinos crossing mountains
- Moon-skimming neutrinos
- …

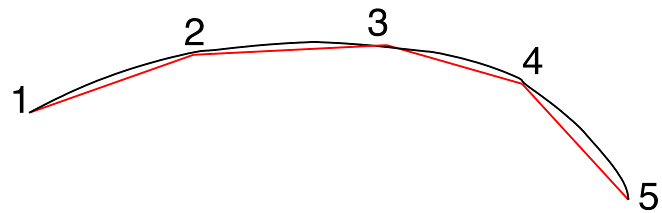


B. EAS starting in air & arriving in dense medium

Background (or even signal) for UHECR/ν detection in buried neutrino arrays

E-field calculation: Full MC of shower + ZHS algorithm

- Model shower particle trajectory as **small straight tracks** at constant speed:



- E-field of each track obtained with well-known **ZHS formula** (1st principles):

$$\mathbf{E}_{\rm ZHS}(\mathbf{x},\omega) = \frac{e\mu_r i\omega}{4\pi\epsilon_0 c^2}\frac{e^{ikR}}{R}\mathbf{v}_\perp\frac{e^{i\mathbf{k}\cdot\mathbf{v}t_1}}{i(\omega-\mathbf{k}\cdot\mathbf{v})}\left[e^{i(\omega-\mathbf{k}\cdot\mathbf{v})t_2} - e^{i(\omega-\mathbf{k}\cdot\mathbf{v})t_1}\right]$$

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

in ice

- Radiation from **non-cancellation** of E-field from adjacent points of consecutive tracks due to:
  - different speeds and/or directions and/or **refractive index of media**
- Tracks obtained with full Monte Carlo: ZHAireS or ZHS MC code.

- Succesfully applied to the prediction of:
  - Askaryan radiation (showers in dense media) ⟶ J.A-M et al. PRD **84**, 103003 (2011)
  - Geomagnetic + Askaryan (showers in air) ⟶ J. A-M et al. APP **35**, 325 (2012)
  - Synchrotron & Cherenkov radiation ⟶ A. Taboada Master's thesis (2015), D. Garcia-Fernandez et al. PRD **87**, 023003 (2013)

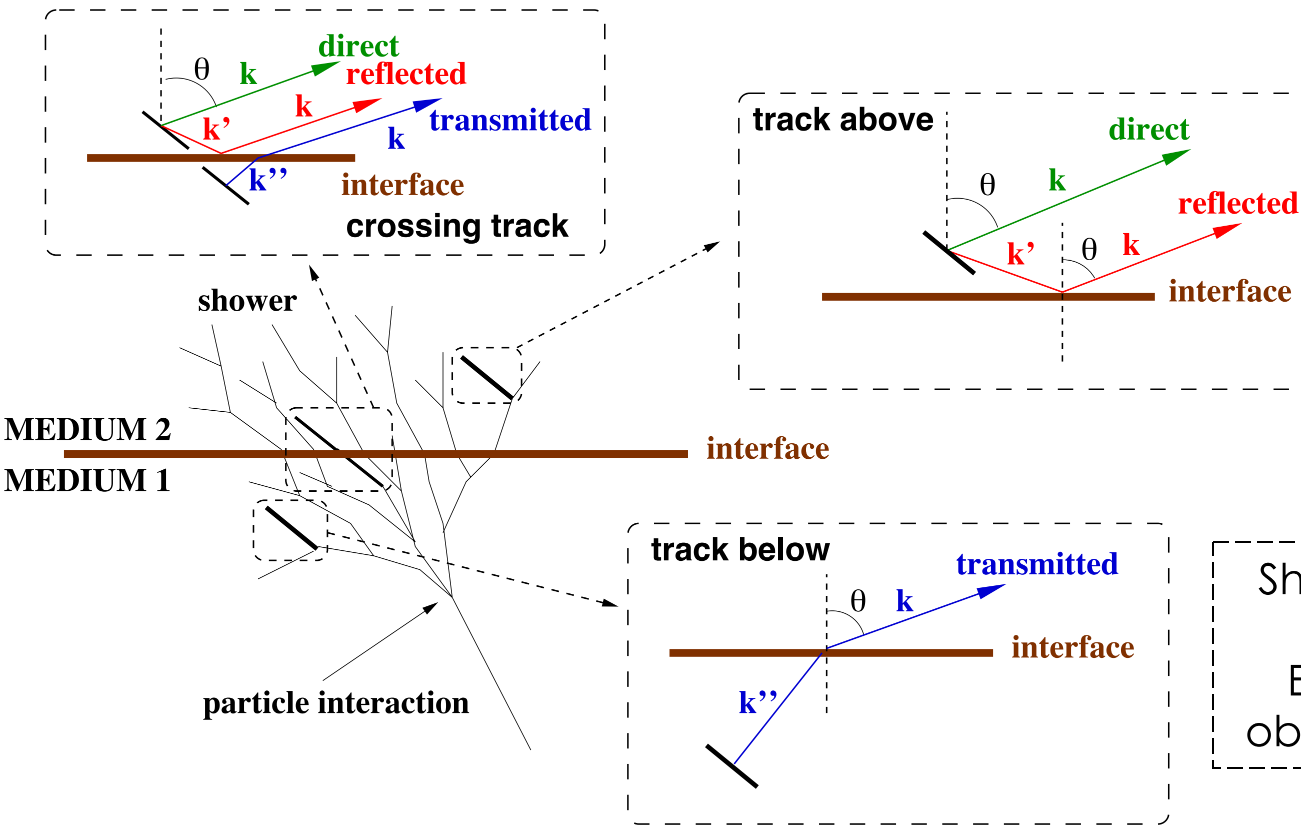
Methodology: the ZHS-TR algorithm

Contributions to radiation: observer in MEDIUM 2 at direction (k)

- **Refracted** radiation from tracks **below** interface
- **Direct** & **reflected** radiation from tracks **above** interface
- **Direct**, **reflected** & **reflected** from tracks **crossing** (splitted) at interface

Inteference between radiation from tracks above, below & crossing boundary

Transition Radiation: non-cancellation of emission just before boundary & just after tracks crossed boundary

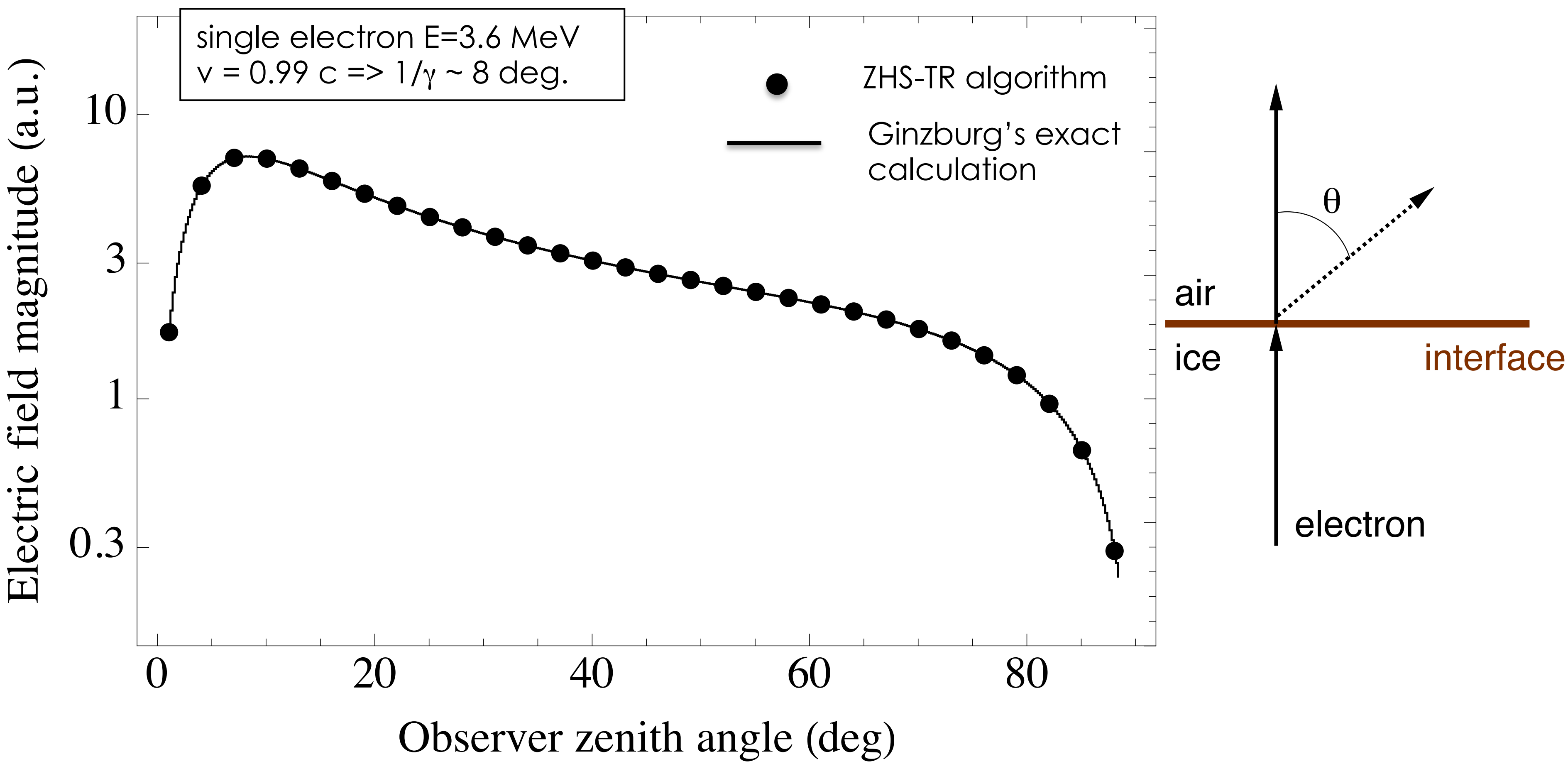


Shower simulated with full Monte Carlo (ZHS)
E-field from each track obtained with ZHS formula

methodology as in C.W. James et al. PRE **84**, 056602 (2011) (applied to single electron using endpoints algorithm)

Transition Radiation: single electron

- Check validity of ZHS-TR algorithm:
  - E-field from single electron from -inf to inf crossing from ice to air
  - Agreement with "mirror charge" calculation of TR by Ginzburg [1]



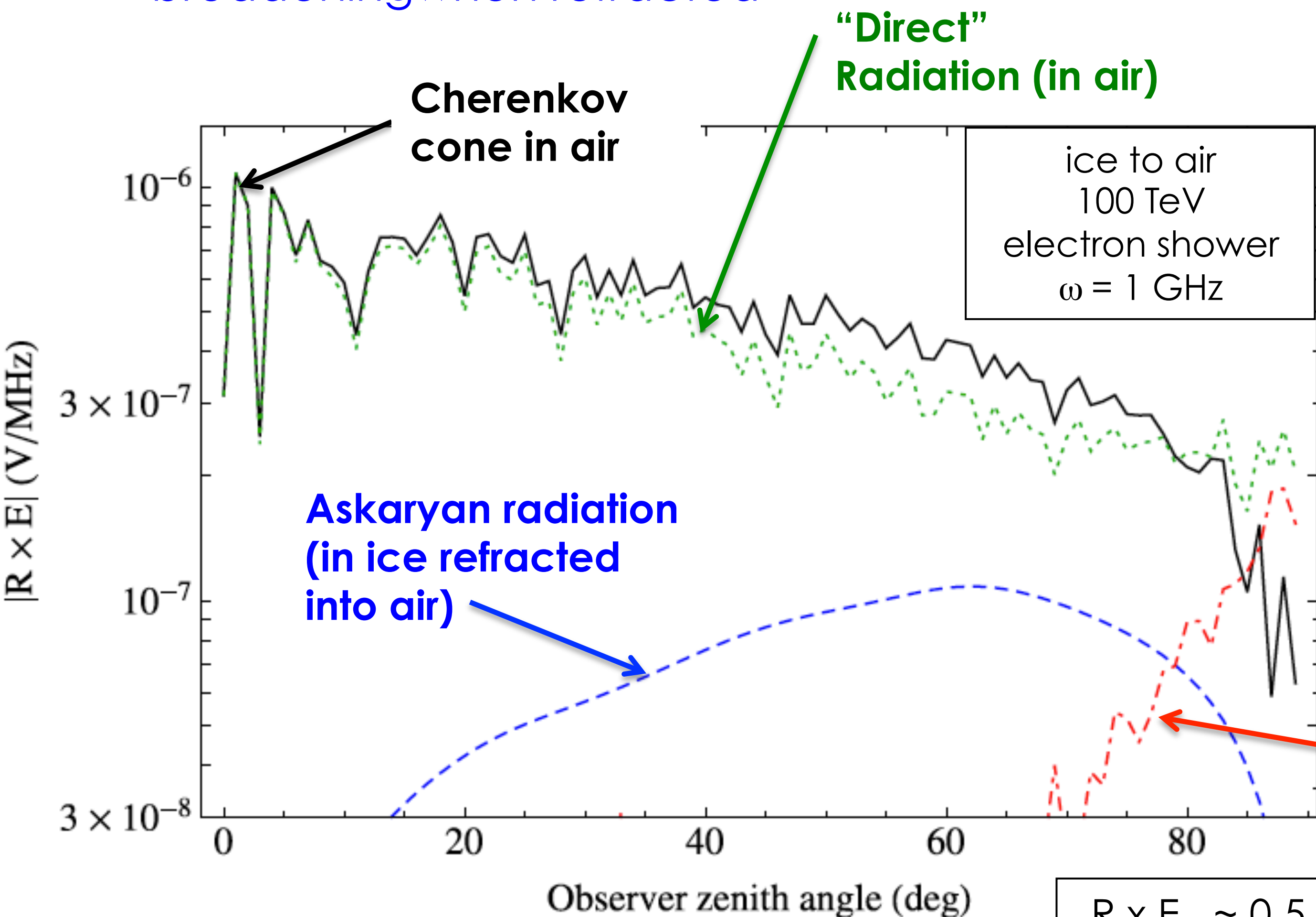
[1] Ginzburg & Tystovich Transition Radiation & Transition Scattering, IOP Publishing, 1990.

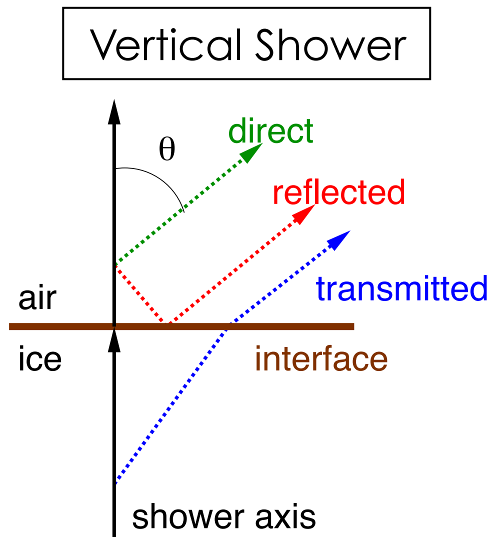
Showers from ice to air
Observer in air

Showers simulated with full Monte Carlo (ZHS)
E-field from each track obtained with ZHS formula

θ distribution, ice ⟶ air, vertical shower

- Broad angular distribution (even at GHz freqs) => wide solid angle
- Direct contribution in air dominates emission for vertical showers
- Cherenkov cone in ice suffers total internal reflection & broadeningwhen refracted

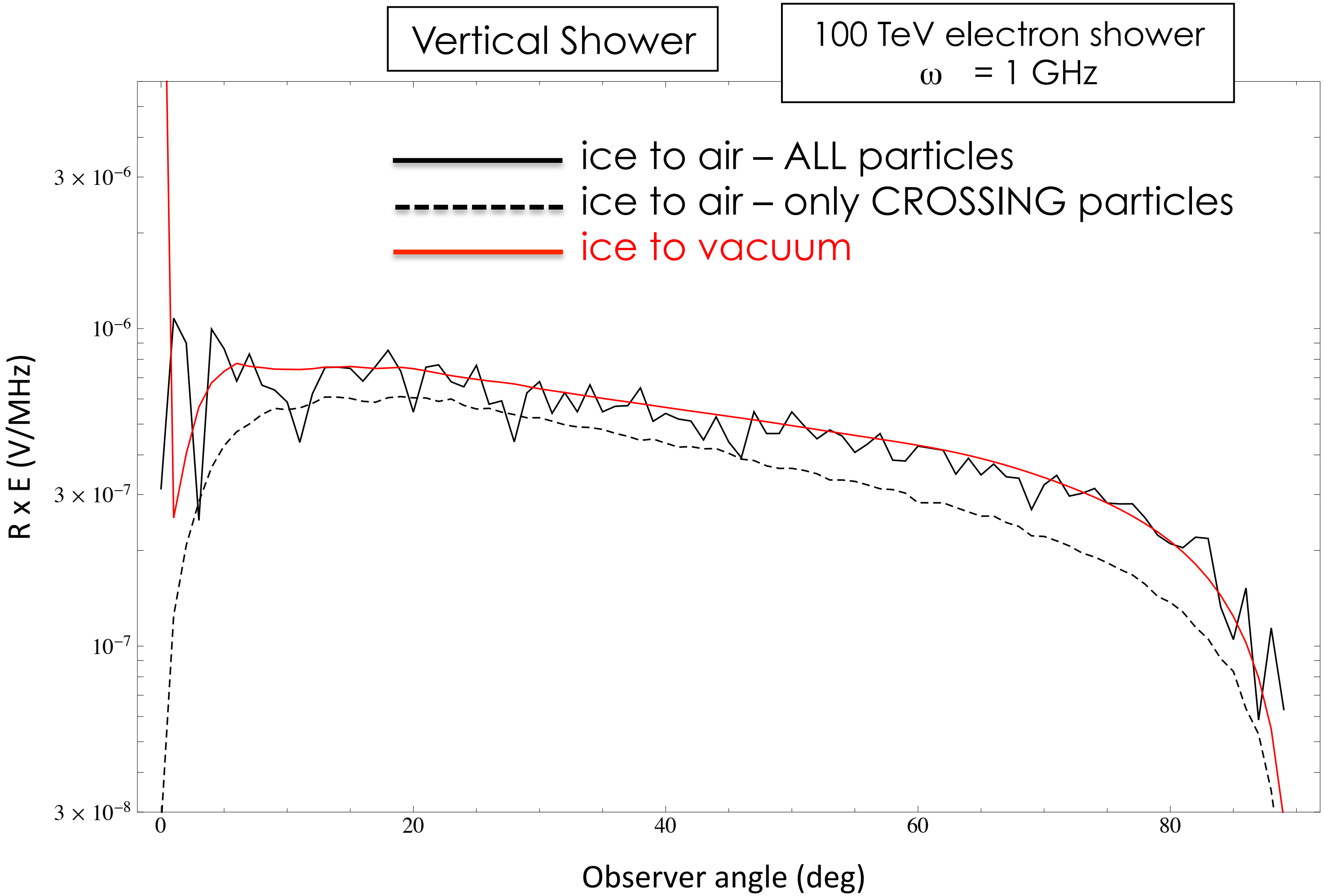




$R \times E_w \sim 0.5\ \mu V/MHz$ @ 100 TeV

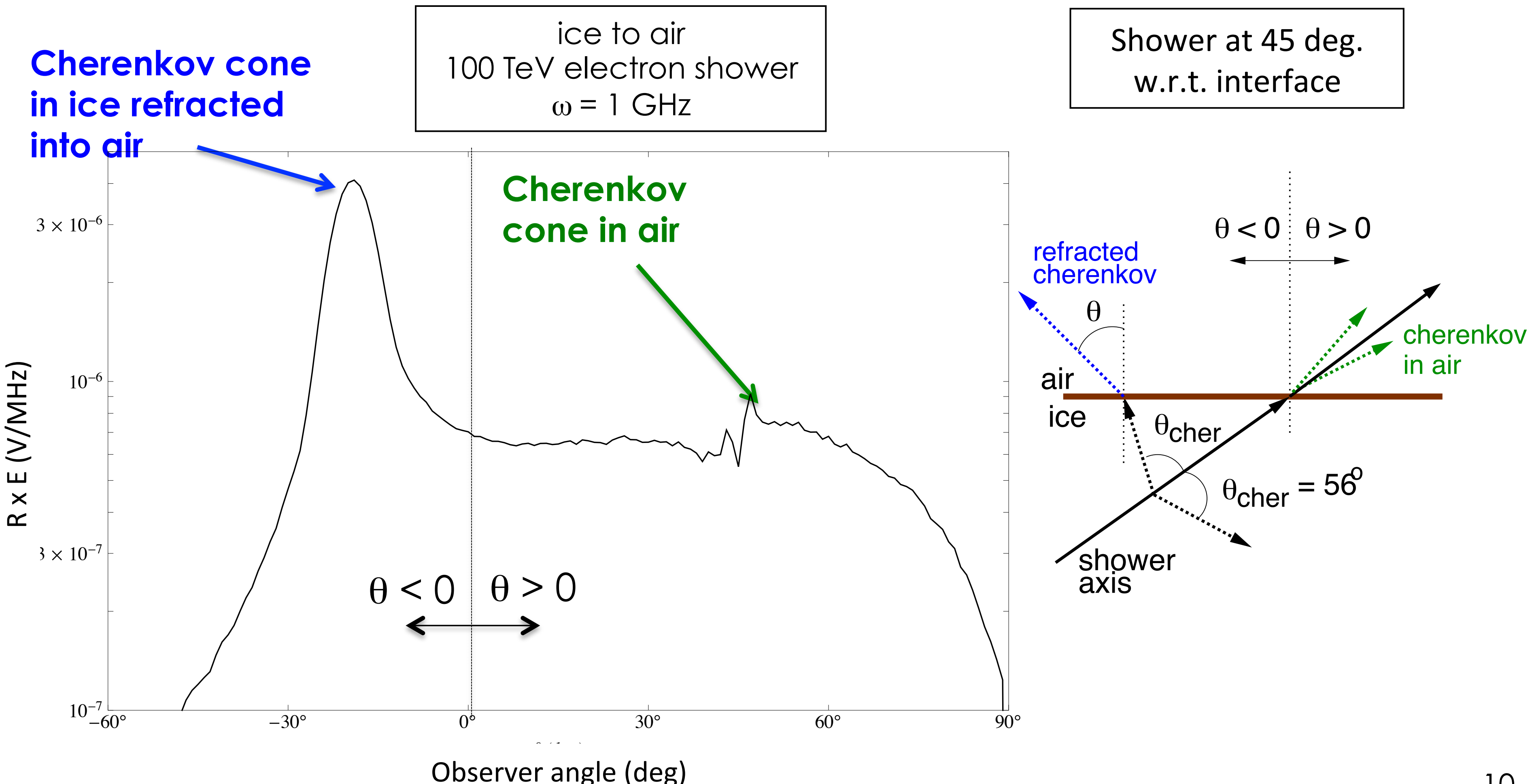
Contribution from crossing particles

- Crossing tracks account for a significant fraction of emission.
- Radiation from ice to vacuum similar to that from ice to air (except for at very low angles)



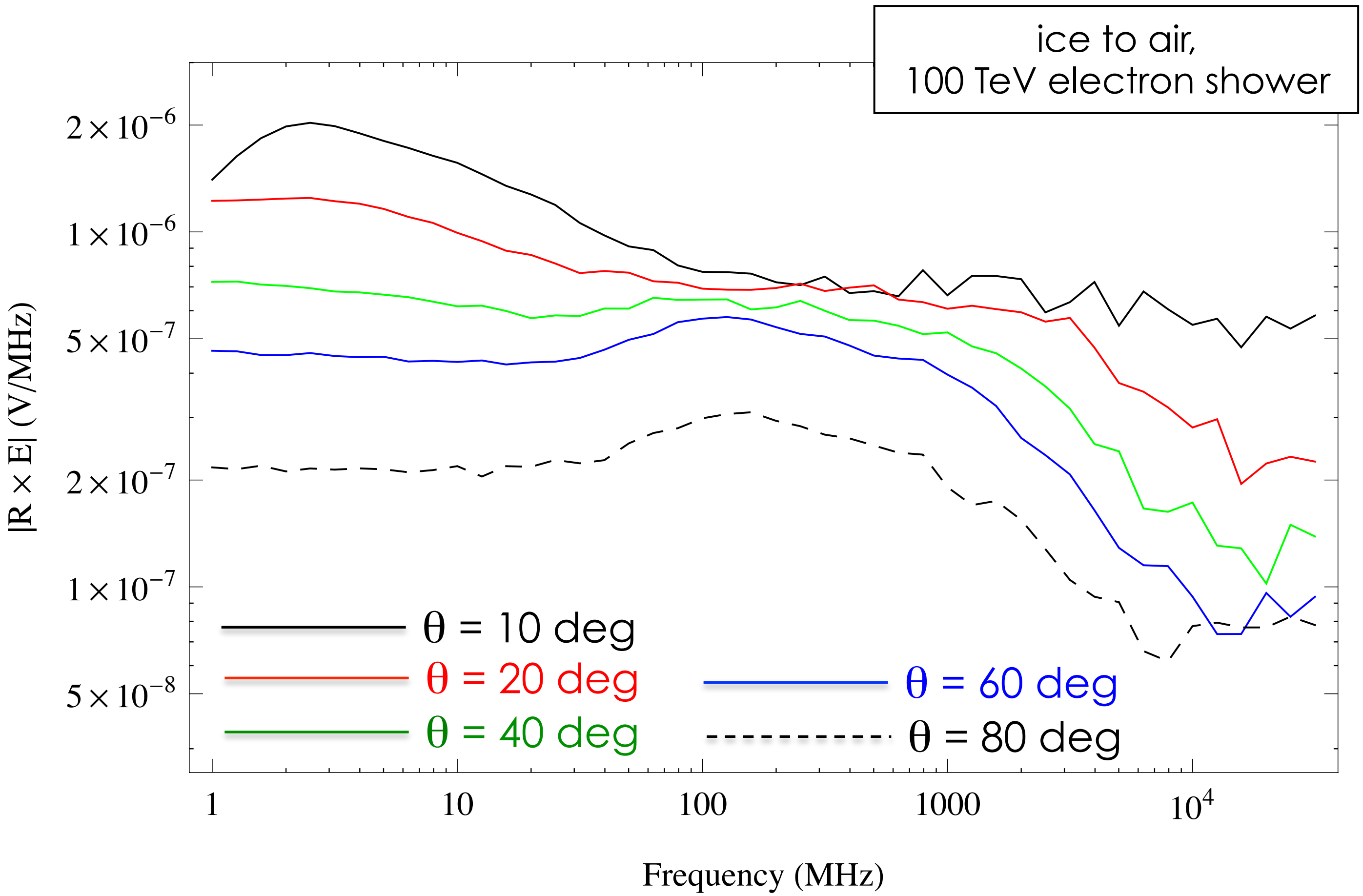
θ distribution, ice $\rightarrow$ air, inclined shower

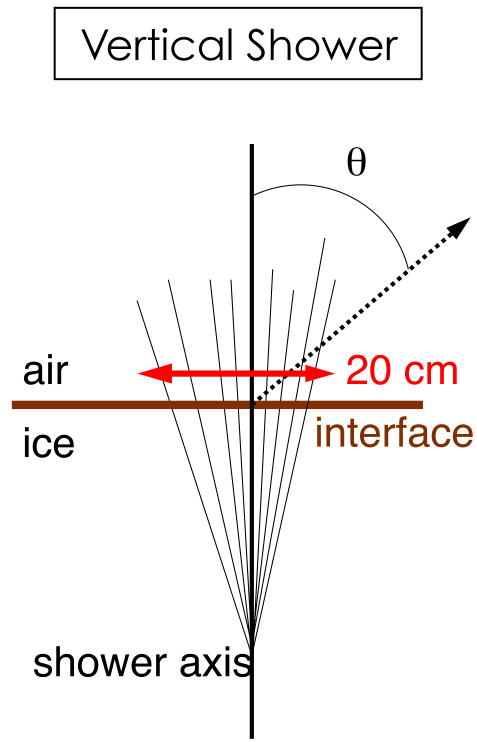
- Broad angular distribution => wide solid angle for detection
- Cherenkov cone in ice refracted into air: dominates emission in a narrow angular range



ω-spectrum ice ⟶ air, vertical shower

- Emitting source (shower from ice) is compact at interface => Coherence up to 1 GHz => broadband emission

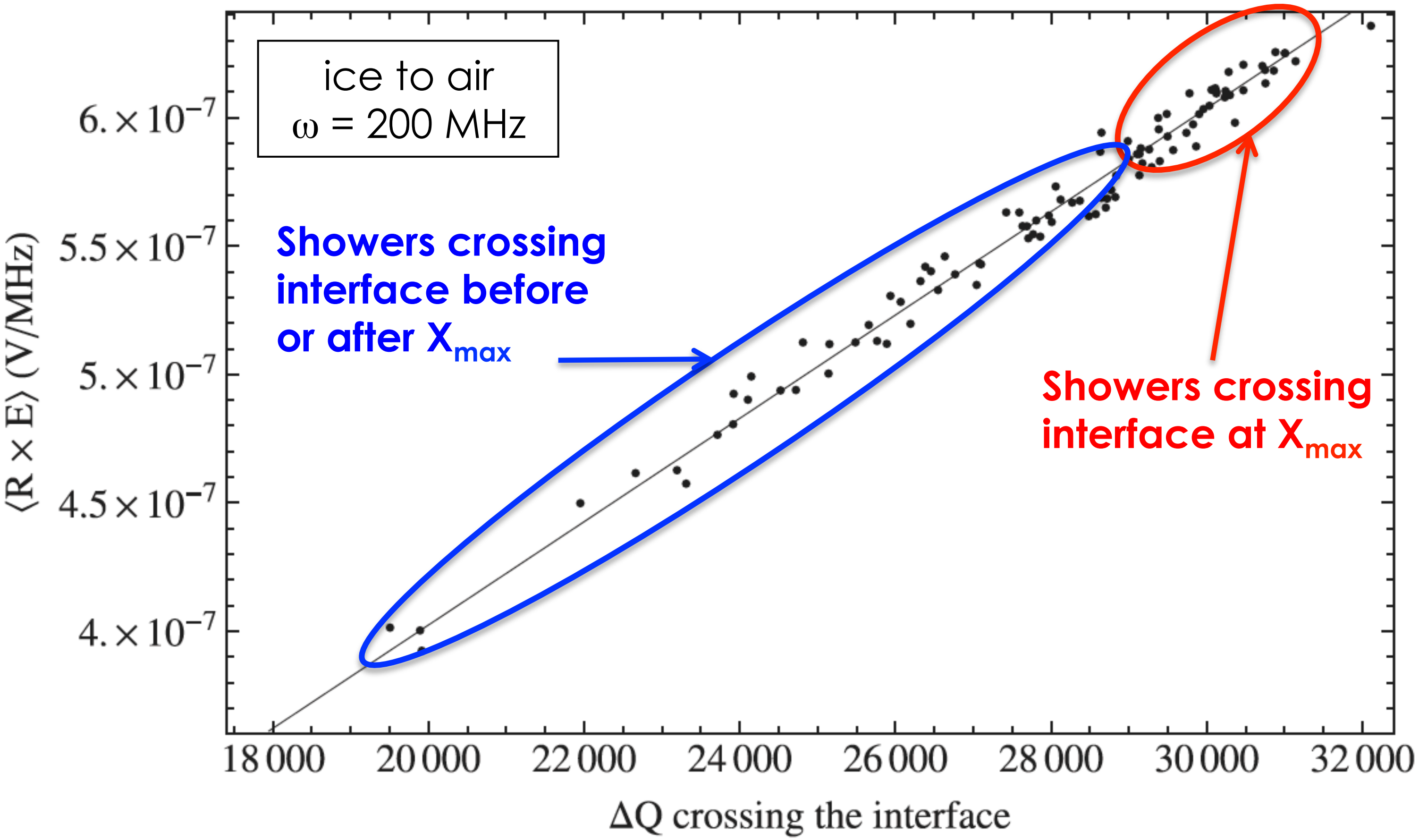




Energy scaling of radiation

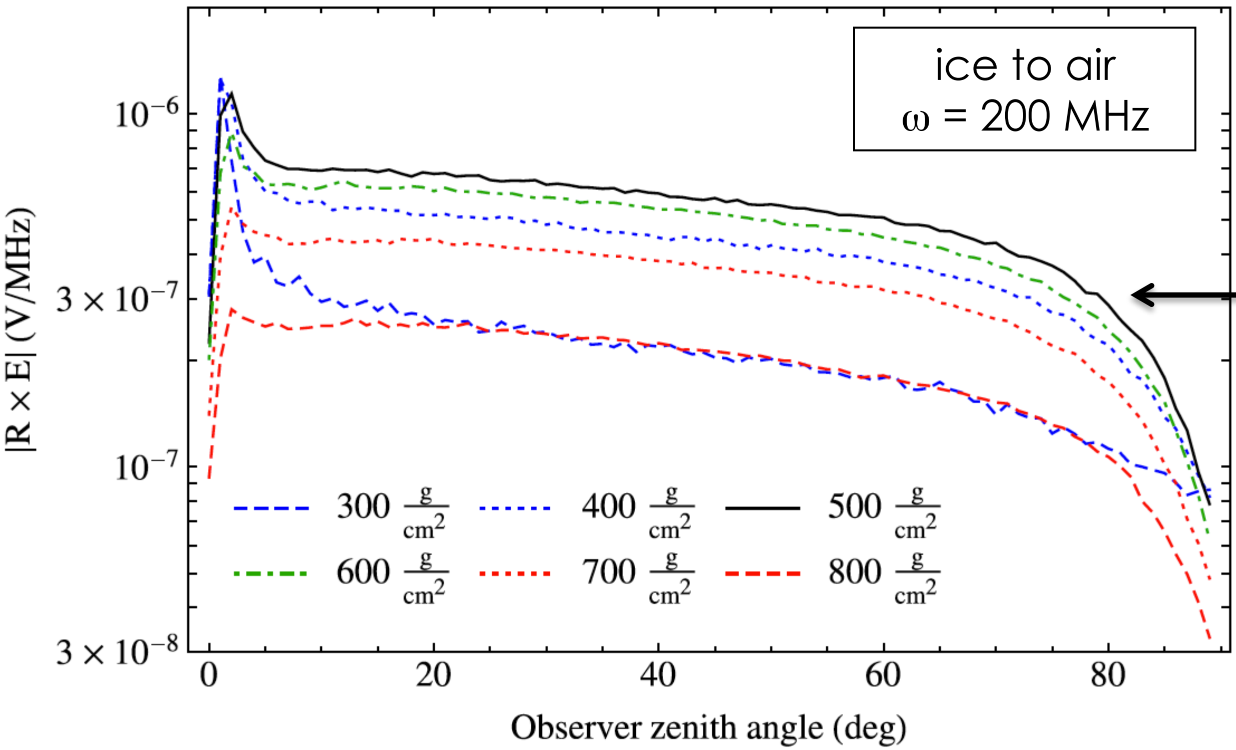
- E-field is linear with excess charge crossing interface

100 TeV electron showers initiated at **fixed distance to interface**



Energy scaling of radiation

- E-field scales with shower energy but:
  - Large fluctuations of E-field in showers of fixed energy due to variable distance to interface
  - LPM effect in em showers stretches them longitudinally, further increasing fluctuations



100 TeV electron showers initiated at **different distances to interface**

Black line: Shower crossing interface at X_{max} => max. emission

- Difficult to determine primary particle energy (unless distance of primary interaction to interface can be inferred)

Detectability of neutrinos through TR

- **Energy threshold** is "relatively low":

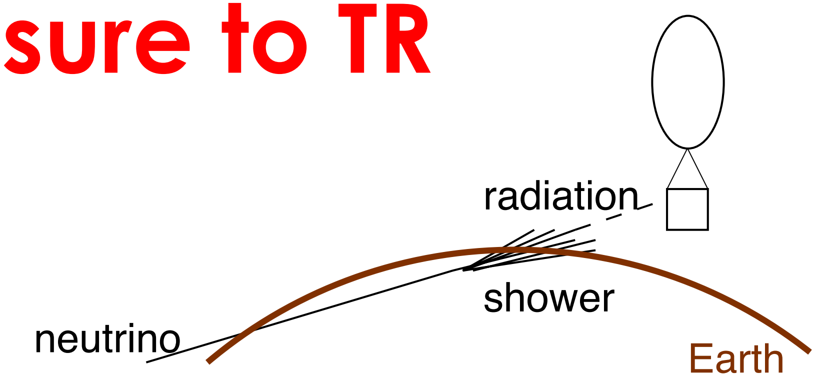
$$E_\nu^{\rm min} \simeq 2-4\times 10^{17}\ {\rm eV}\left(\frac{d}{1\ {\rm km}}\right)\left(\frac{100\ {\rm MHz}}{\Delta\nu}\right)\left(\frac{A_{\rm min}}{150\ \mu{\rm V/m}}\right)^{*}$$

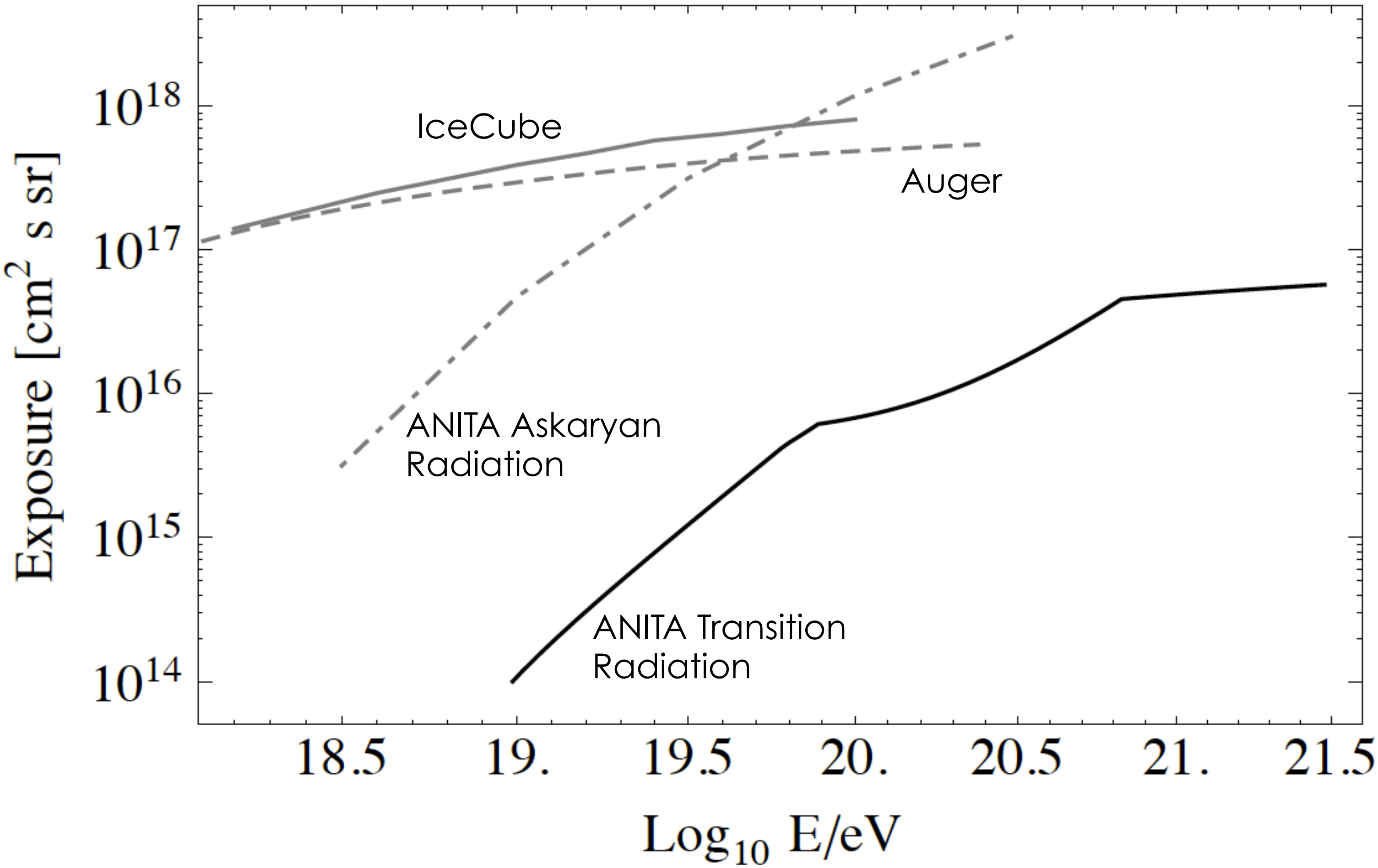
- **Broad angular distribution** => large solid angle for detection.
- **Coherence** up to few GHz => broad-band emission.
- **Polarized signal** [**k** x (**k** x **v**)] => information on shower direction.
- **Linear scaling with shower energy** … but difficult to determine energy since shower can cross boundary at any stage of longitudinal development
- Shower needs to cross at depth where number of particles is large => **small effective volume** for ν detection for the particular geometry of a high-altitude ballon.

*Assuming ν-induced shower crosses interface close to X_{max}

Example: ANITA exposure to TR

- Estimated exposure for detection of Earth-skimming neutrinos through Transition Radiation in ANITA





P. Motloch et al. in preparation

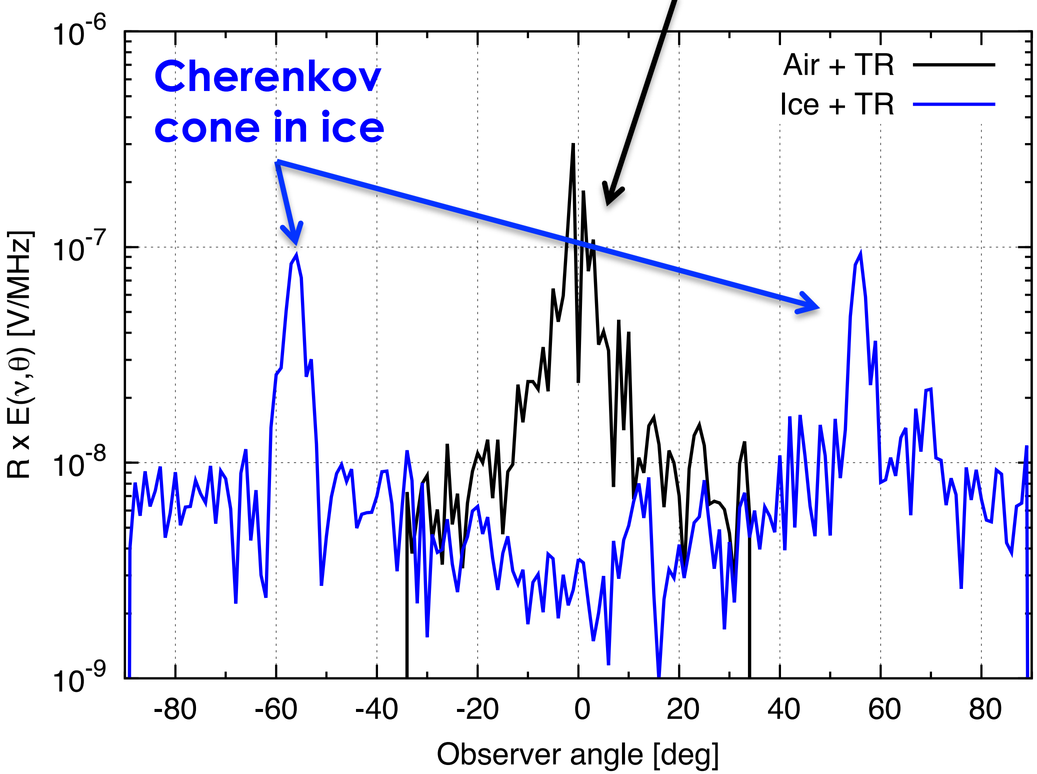
Showers from air to ice
Observer in ice

θ distribution air → ice, vertical shower

- Rich angular distribution:
  - Cherenkov cone in air refracted into ice + Cherenkov cone in ice
- Cherenkov cone in ice dominates emission around ~ 56 deg.

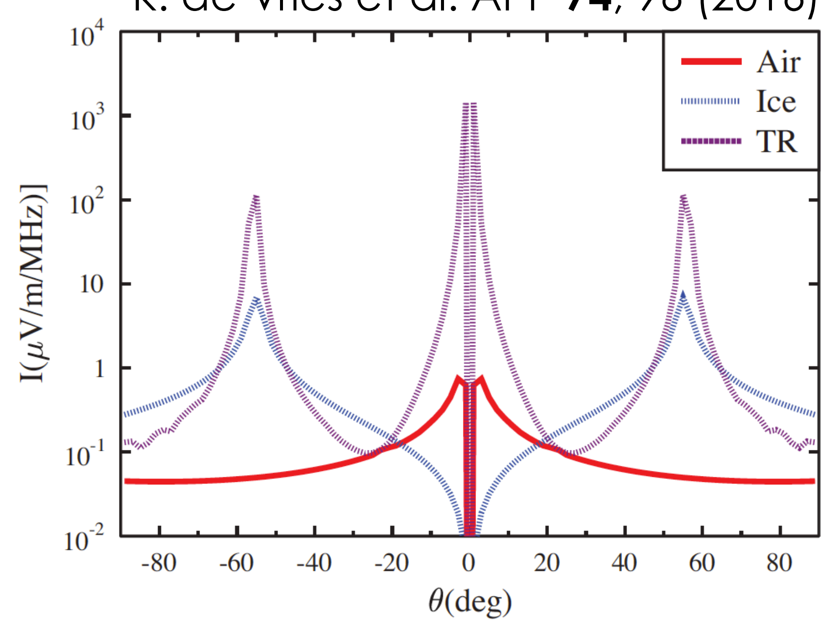
air to ice
10 TeV electron shower
ω = 1 GHz

Cherenkov cone in air refracted into ice



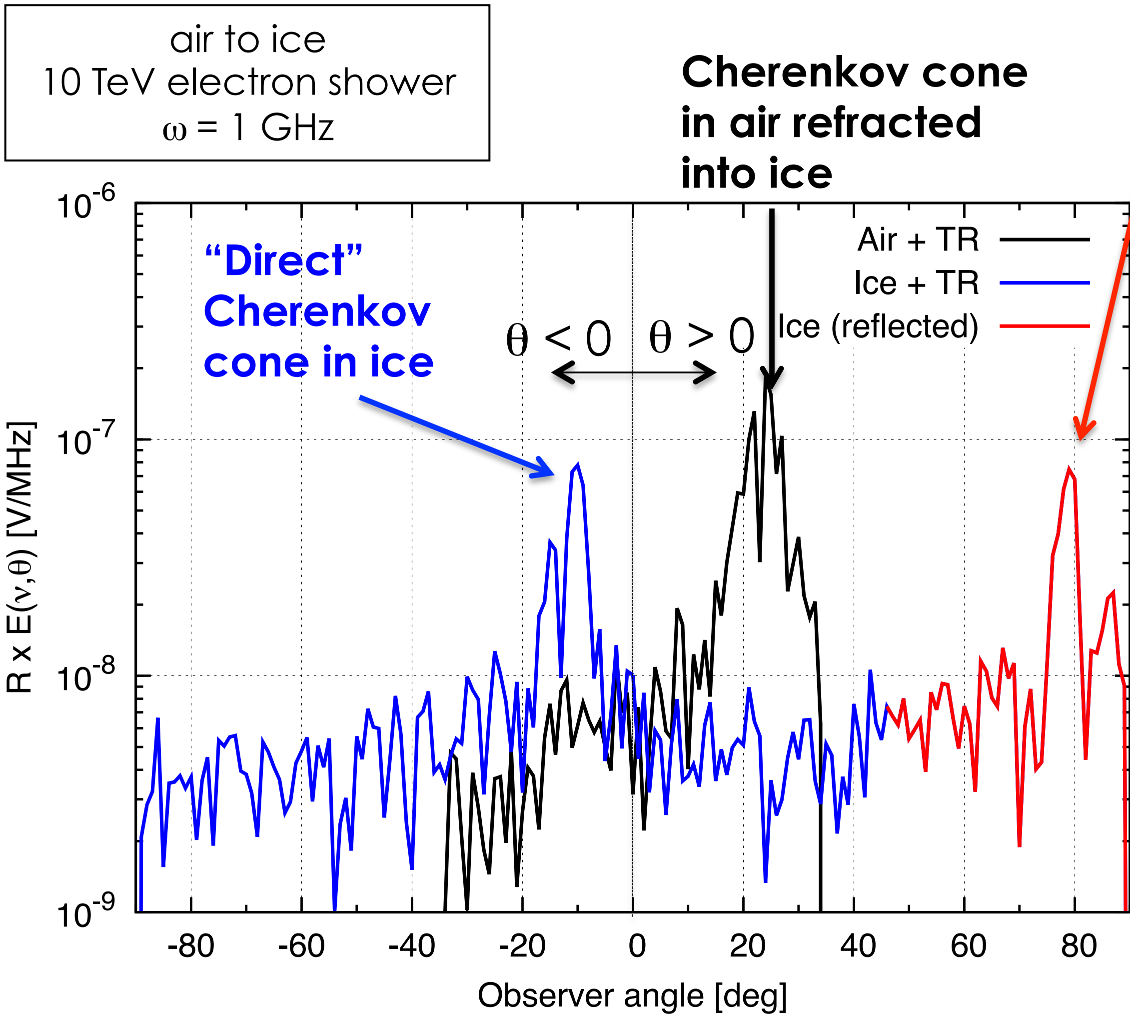
Vertical Shower

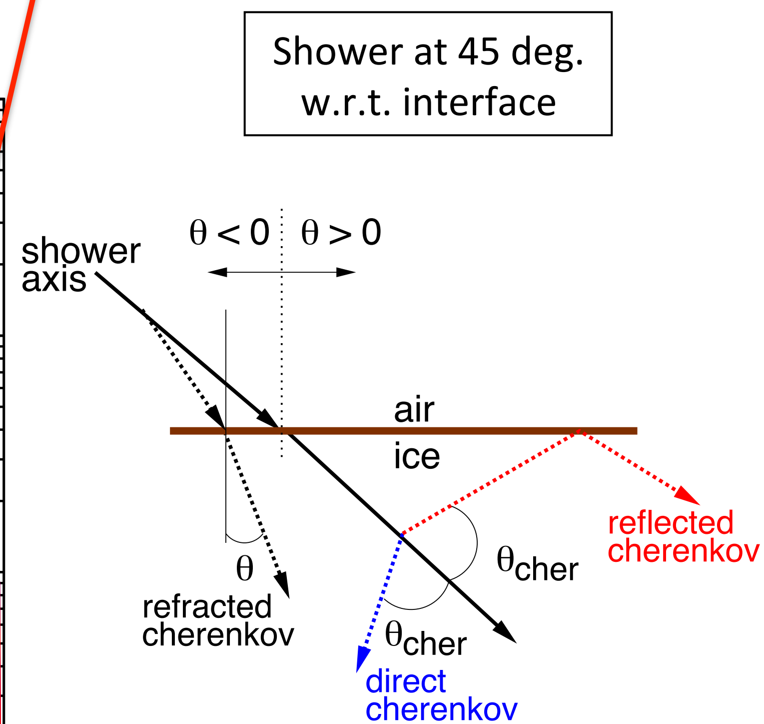
Analytical calculation
K. de Vries et al. APP **74**, 96 (2016)



θ distribution, air ⟶ ice, inclined shower

- Rich angular distribution:
  - Cherenkov cone in air refracted into ice
  - Cherenkov cone in ice

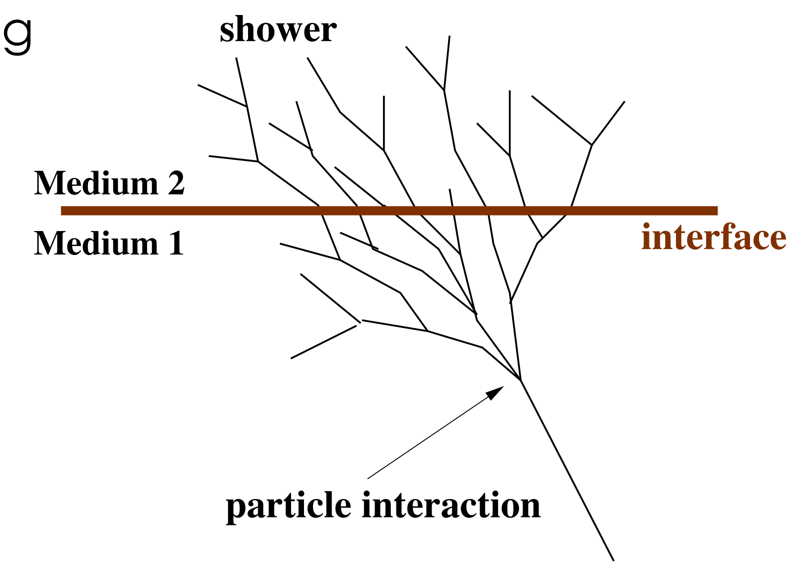




Summary & Outlook

P. Motloch et al.
Phys. Rev. D **93**, 04310 (2016)

- **Full Monte Carlo + ZHS** ("microscopic") calculation of radiation emitted in particle showers crossing interface between two dielectric media:
  - from dense media to air
  - from air to dense media



- **Characterization of properties:**
  - ω-spectrum & θ distribution
  - shower energy dependence
  - …

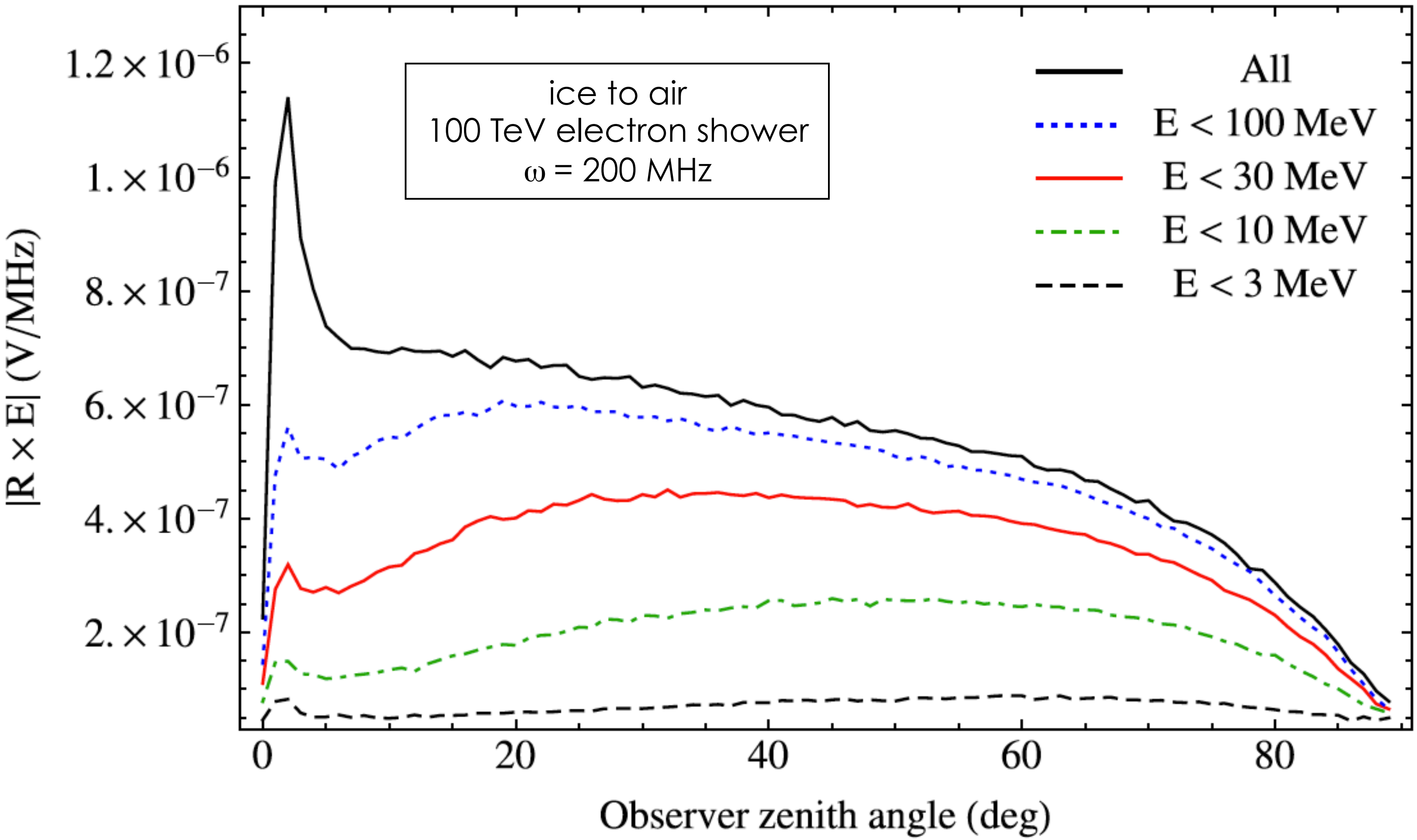
- Studied **pros & cons of Transition Radiation** as detection technique for UHE neutrinos – the case of ANITA & Earth-skimming neutrinos

- Tool to study potential of TR as detection technique for UHE neutrinos
  - Implement ZHS-TR in ZHAireS (ν-induced showers can be simulated)
  - Perform studies of optimal geometries, frequencies,… for TR detection

Backup slides

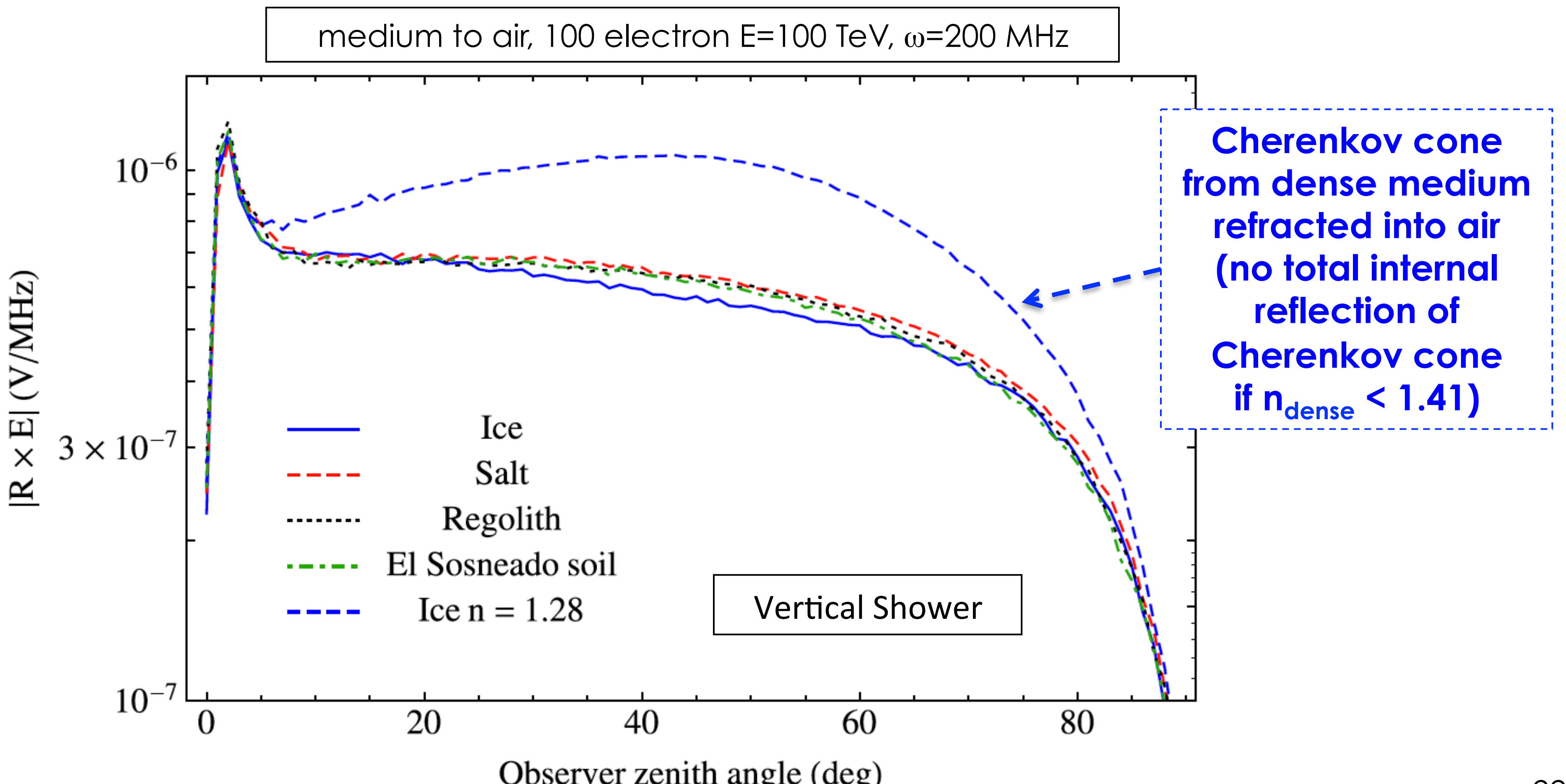
Dependence on particle threshold

- Highest energy particles responsible for forward peak at $\theta \sim 0$ deg.
- Particles with E < 3 MeV contribute very little



Radiation from different media → air

- E-field comparable for ice, salt, regolith & ice.
- If refractive index of dense medium allows refraction of Cherenkov cone => larger emission .



Angular distribution in half the sky

ice to air
100 TeV electron shower
45 deg w.r.t. boundary

(θ, Φ) = observer positions