Radio detection and Ultra High Energy tau neutrino searches

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Neutrinos are the best UHE messengers

Extreme objects GRB, AGN, TDE, magnetars …

Naturally expected because CR reach to 10^{20} eV

Interactions at CR accelerators → Point sources
Interactions on their path (CMB, EGB) → Diffuse

Tau neutrinos are produced in oscillations

Flavor ratio constrains origin (π decay, μ damped, n decay) Fe/p

Tau neutrinos open the Earth Skimming channel

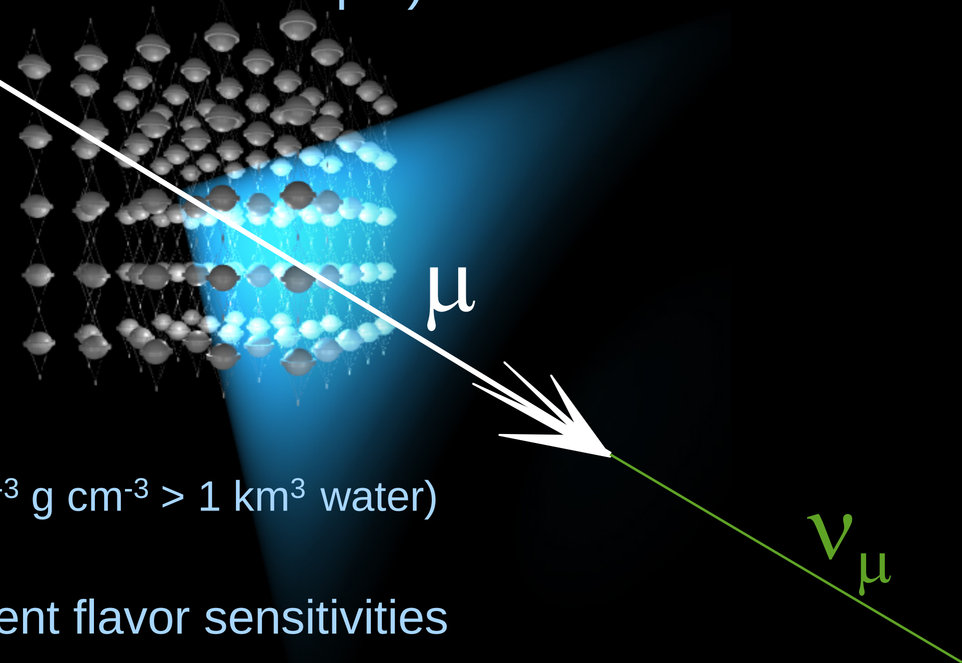
Enhanced exposure
Aperture concentrated in small field of view (point source sensitivity)
Regeneration

Fundamental physics

Cross sections
Oscillations
BSM physics

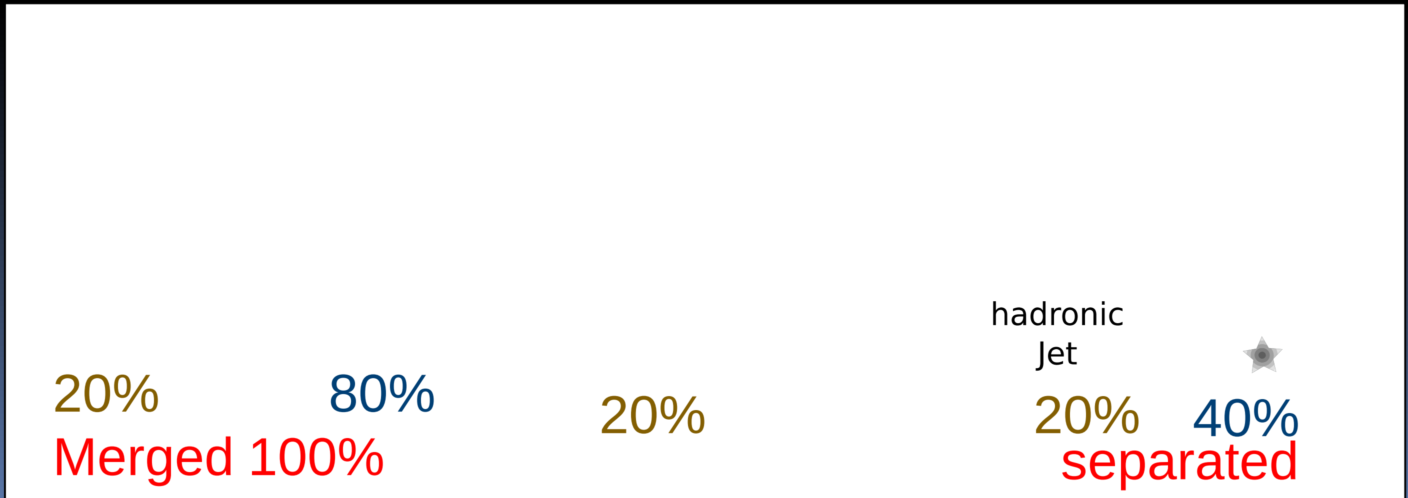
Neutrino detection => Large volumes (larger @ UHE)

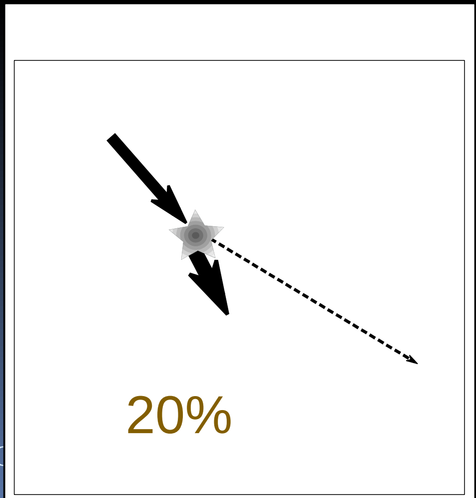
Muon (tau) tracks (in water/Ice: “conventional” technique)



Showers

- conventional (inside volume)
- radio technique
- air showers (3000 km^2·few km height·10^{-3} g cm^{-3} > 1 km^3 water)
- Flavor identification
  - Different energy fractions => different flavor sensitivities
  - Secondary showering of leptons
  - Different shower types that could be identified => (gamma ray exp?)





Alternatives bloom in the last 20 years; two drivers:

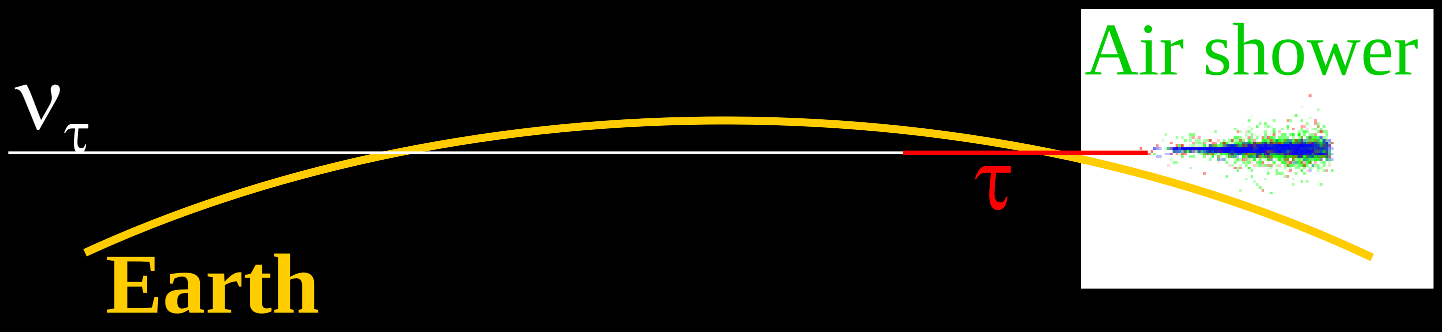
Earth skimming channel for detection

Enhanced for tau neutrinos (expected from oscillations)

Progress in radio

- Technology
- Maturity of radio projects in ice (ARA, ARIANNA, ANITA…)
- Radio for air showers revisited (ANITA, LOFAR, AERA…)
- Simulations (radio in air showers only understood ~2012)

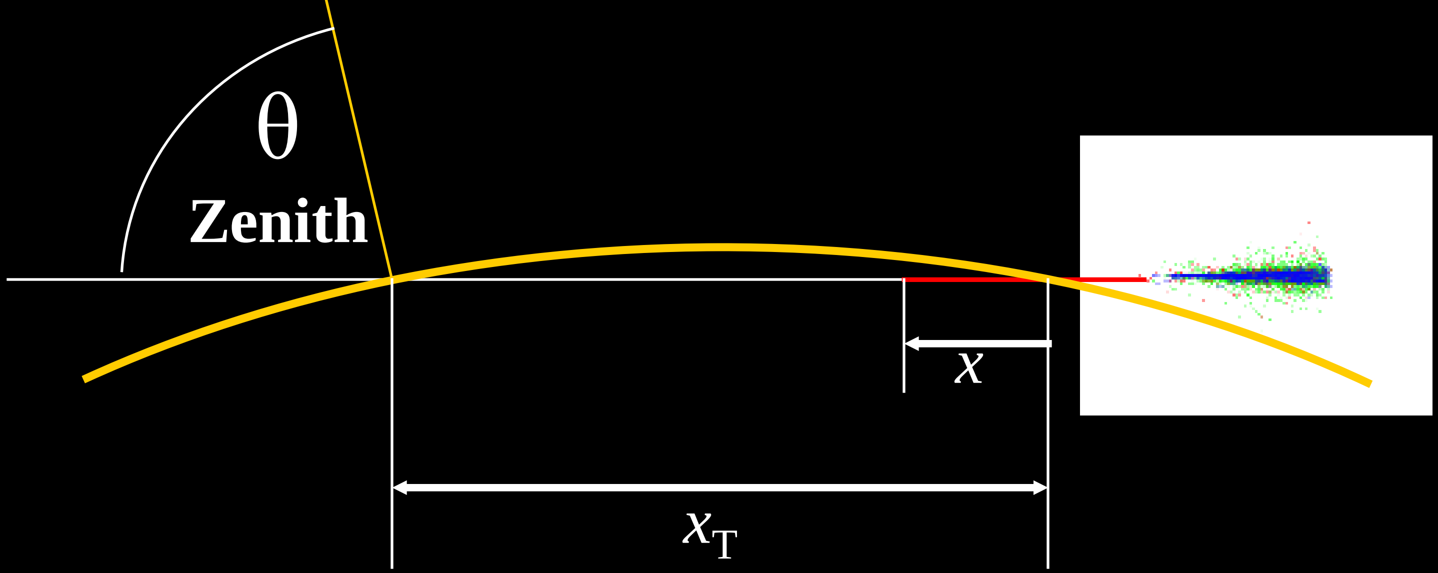
Earth skimming channel for detection



Complex three stage process

- Attenuation through Earth with regeneration: NC
  CC + τ CC
  CC + τ decay
- CC interaction and τ energy loss ➔ rate strongly depends on loss
  range up to 40 km!
- Exit and τ decay in air,
  decay length 50 km EeV ➔ escapes > 10 EeV

Propagation



Very strong θ dependence

Attenuation: $(x_T - x)\, N_A\, \sigma^{CC} > 1$

High E supression > $E_{cut}(\alpha)$

10 PeV	100 PeV	1 EeV	10 EeV	100 EeV
7.6^0	3.3^0	1.4^0	0.6^0	0.26^0

(elevation angle 90-θ)

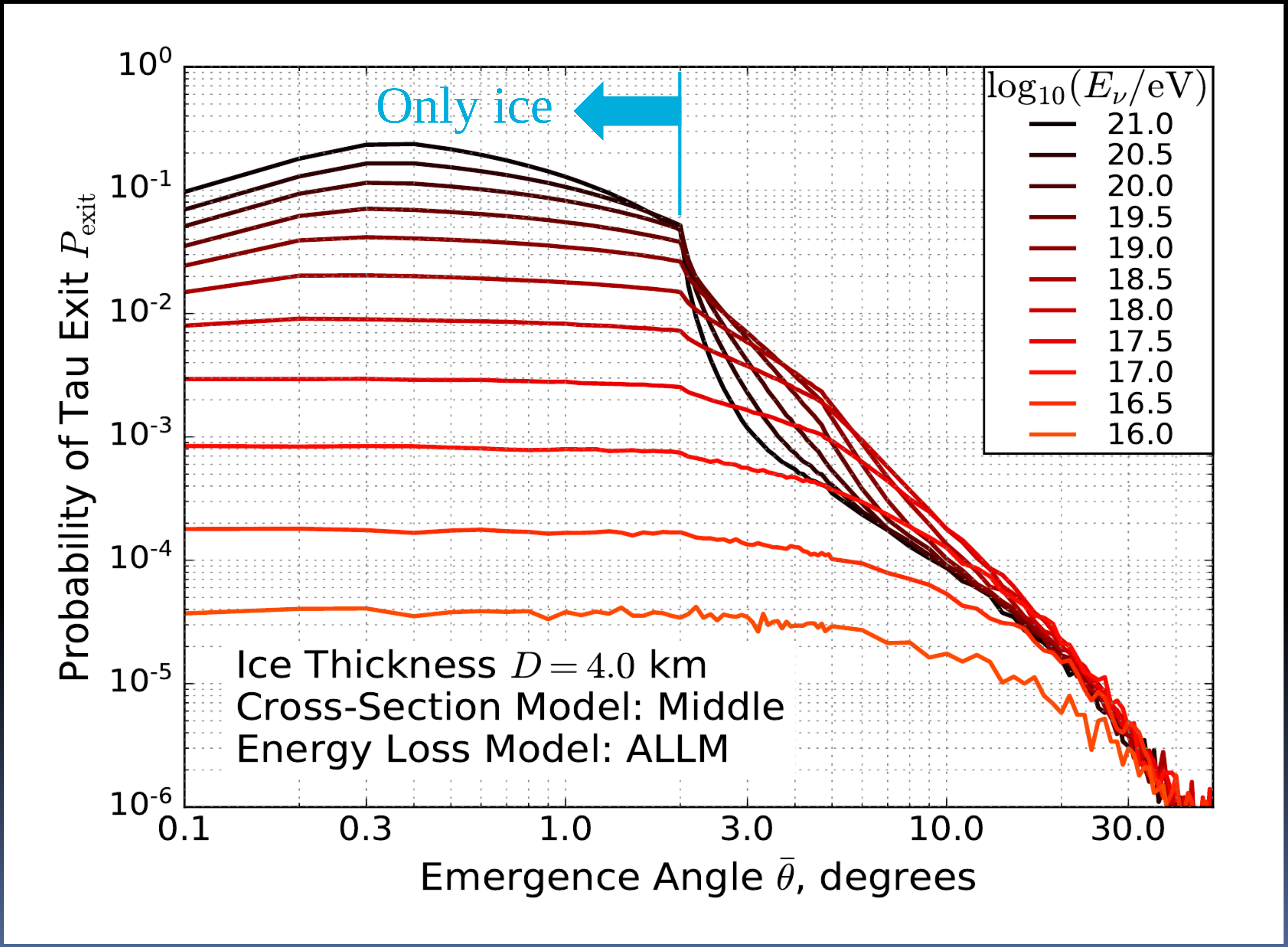
Regeneration: τ decays into ν_τ

pileup(θ) ~ just below the energies that are attenuated

➔ Not that Good for E> 10 EeV

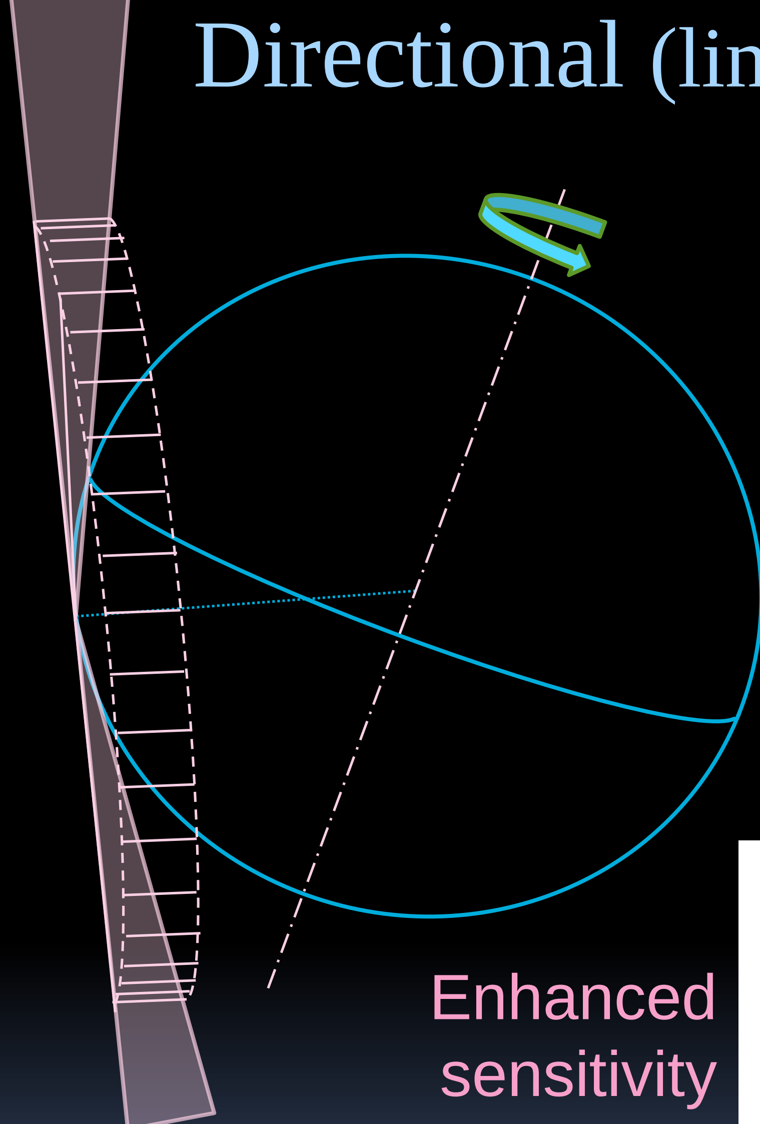
τ exit probability:

it can be very high!
favors low emergence angles

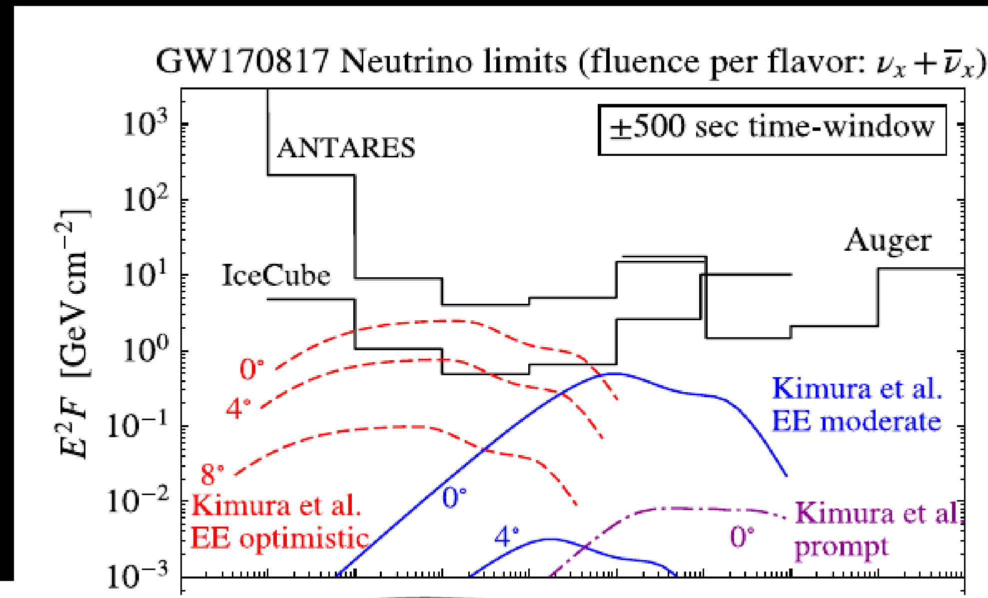


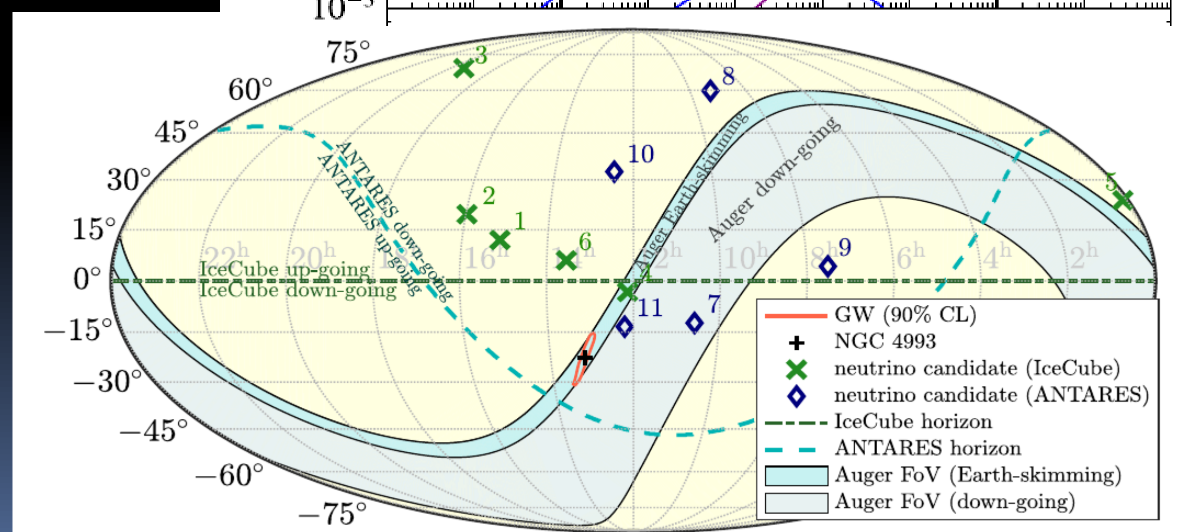
[J. Alvarez Muniz et al. PRD 97 (2018) 2, 023021]

Directional (limited solid angle)



TRANSIENTS ➔ MULTIPLE DETECTORS





Enhanced sensitivity

Good example

P Auger search GW170817

[A. Aab et al. Ap.J.Letts. 850:L35 (2017)]

Coherent radio pulses

Particles radiate (or induce radiation i.e. Cerenkov)

- Radiation adds coherently for low enough frequencies
- Power of coherent radiation scales with (shower particles)^2 UHE!

Interference effects (rich diffraction patterns)

- Shower visualized if well sampled !! (amplitude & phases) flav tagg
- Phased trigger S/N ~ sqrt(N_{ant}) [A.Vieregg et al, JCAP 2(2016) 005, 1504.08006]
- 3D interferometry $\Delta\theta,\Delta\phi<0.1^0$! [H. Schoorlemmer, W.R. Carvalho, arXiv:2006.10348]

Signal: contributions from many (all) shower stages

- Scaling & Reduced fluctuations => good observable

Antennas: cheap

Radio detection: high duty cycle

Main difficulty: dealing with noise

Calculations are key (ZHS)

Maxwell's Equations in transverse gauge

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

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

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

Well known solution,
A gives us the radiated field

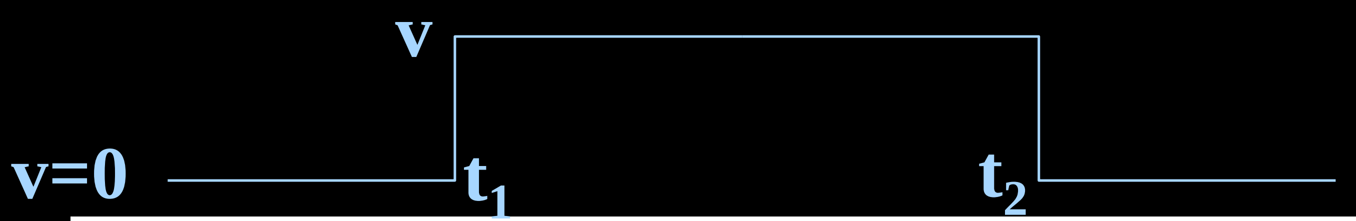
$$\phi = \frac{1}{4\pi\epsilon} \int \frac{\rho(\mathbf{x}', t')}{|\mathbf{x} - \mathbf{x}'|} d^3\mathbf{x}'$$

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

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

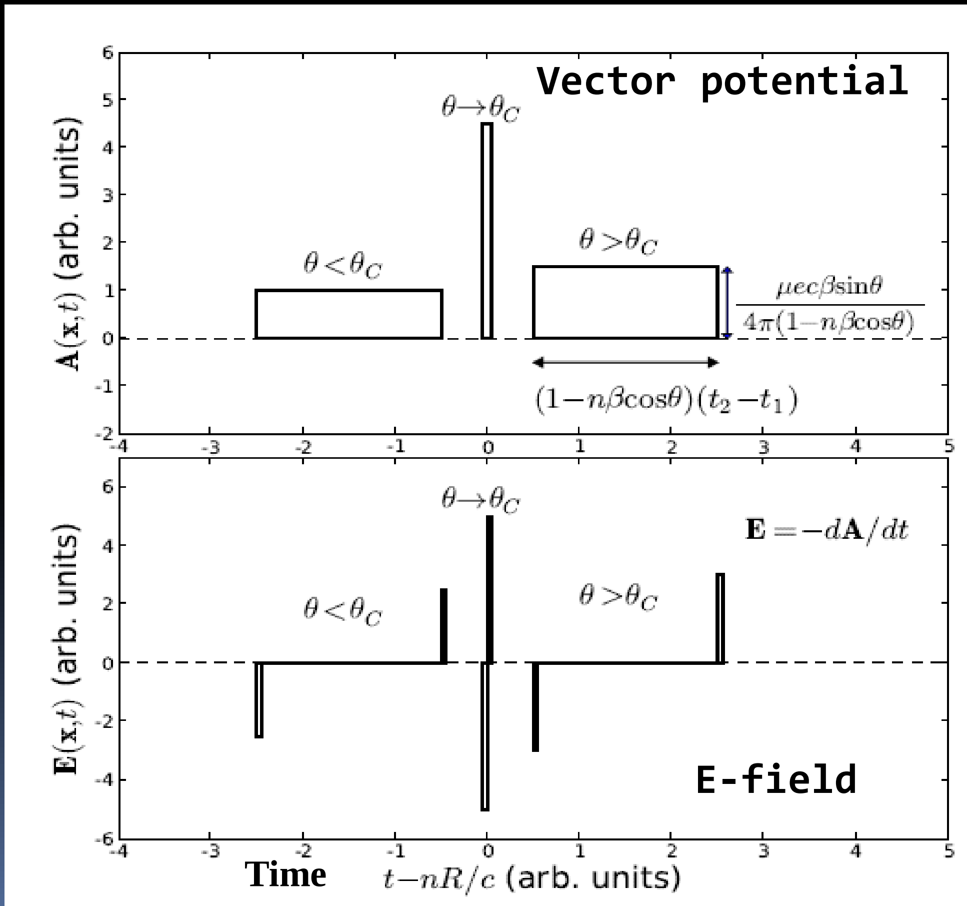
[J. Alvarez Muniz, A. Romero-Wolf, E.Z., PRD 81, 123009 (2010)]

Solve for constant speed subtrack



$\delta t = t_2 - t_1$

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



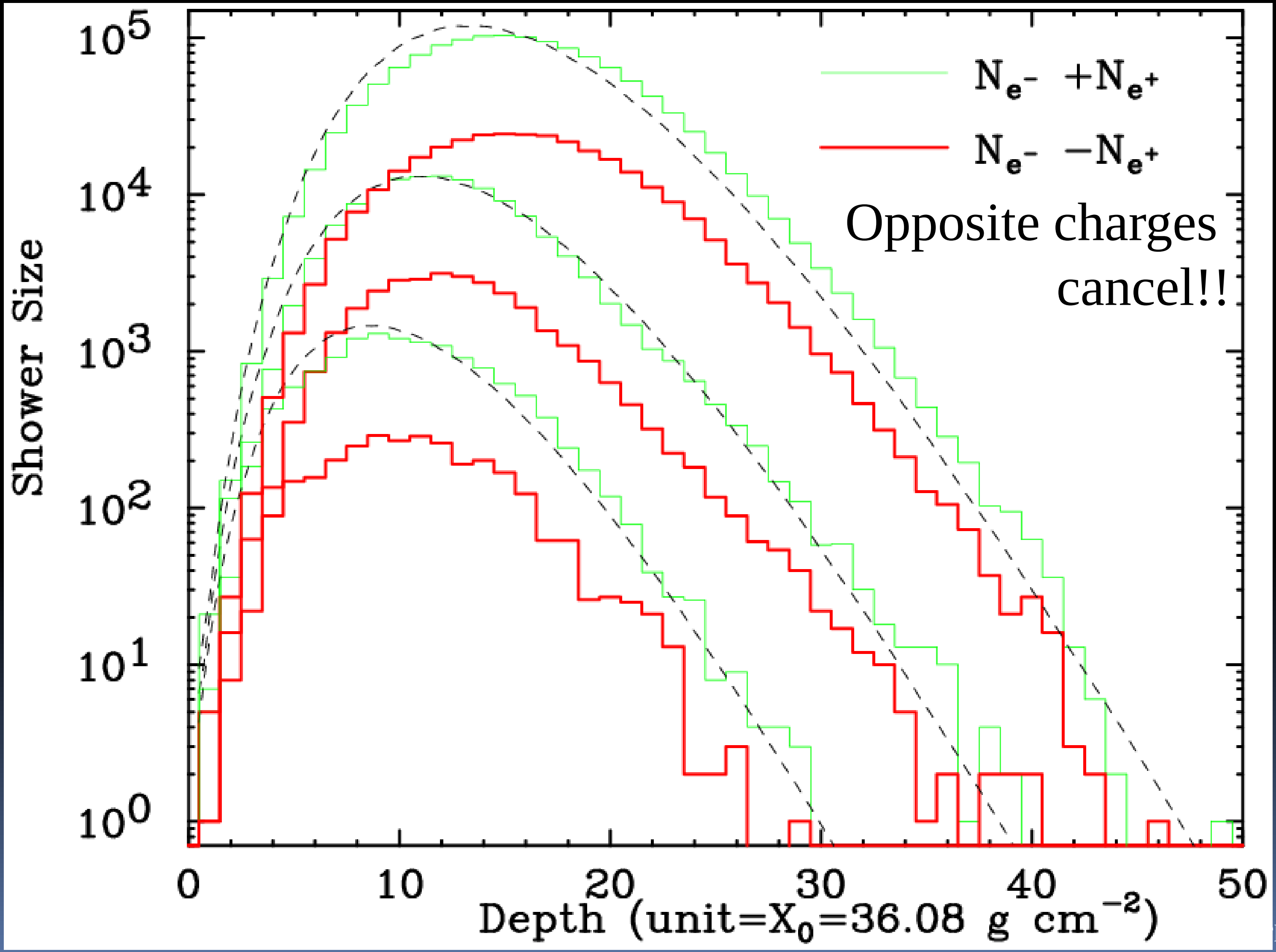
Limit $(1 - n\beta\cos\theta)\delta t \to 0$

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

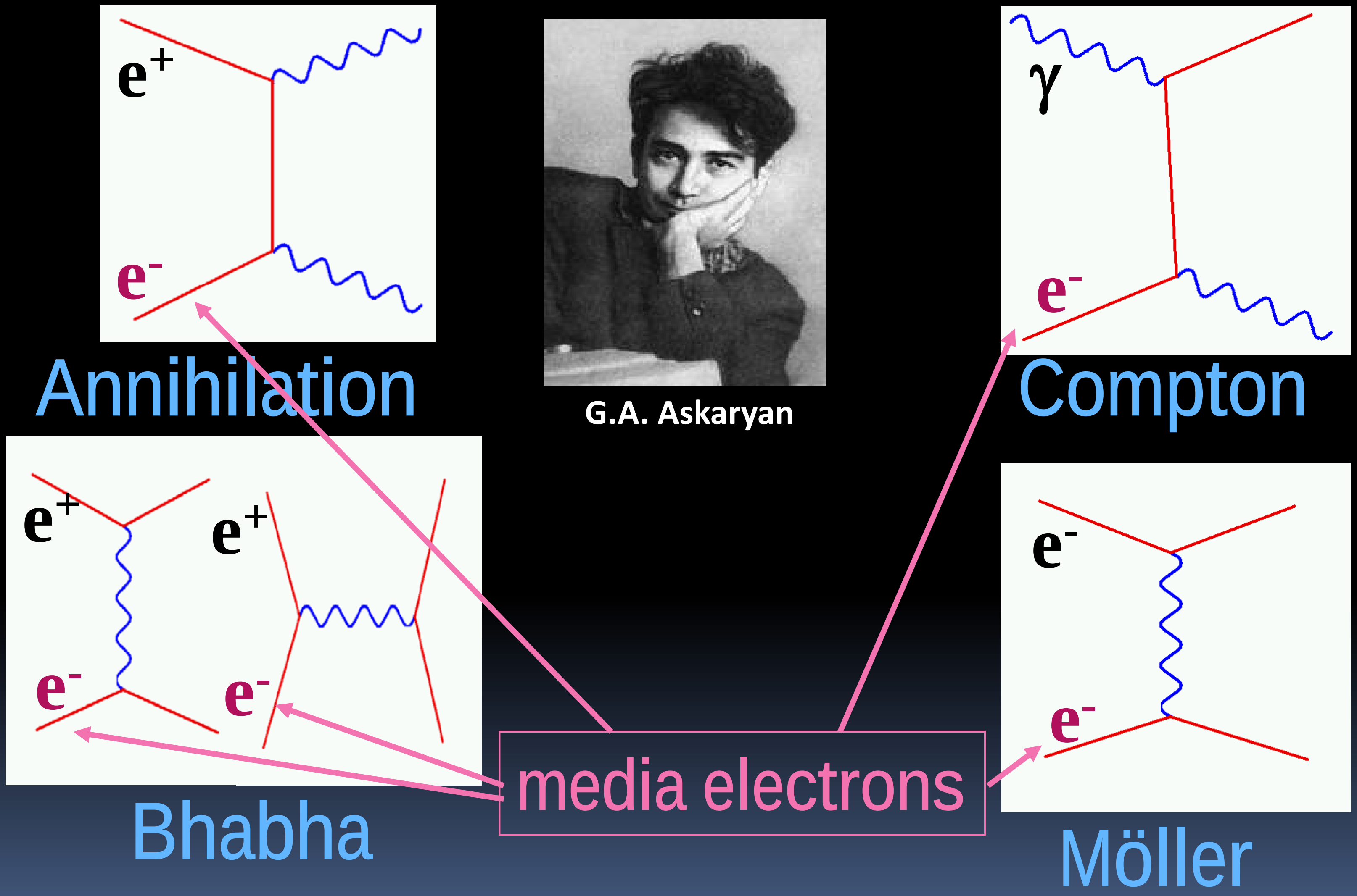
CHERENKOV Radiation

Excess charge

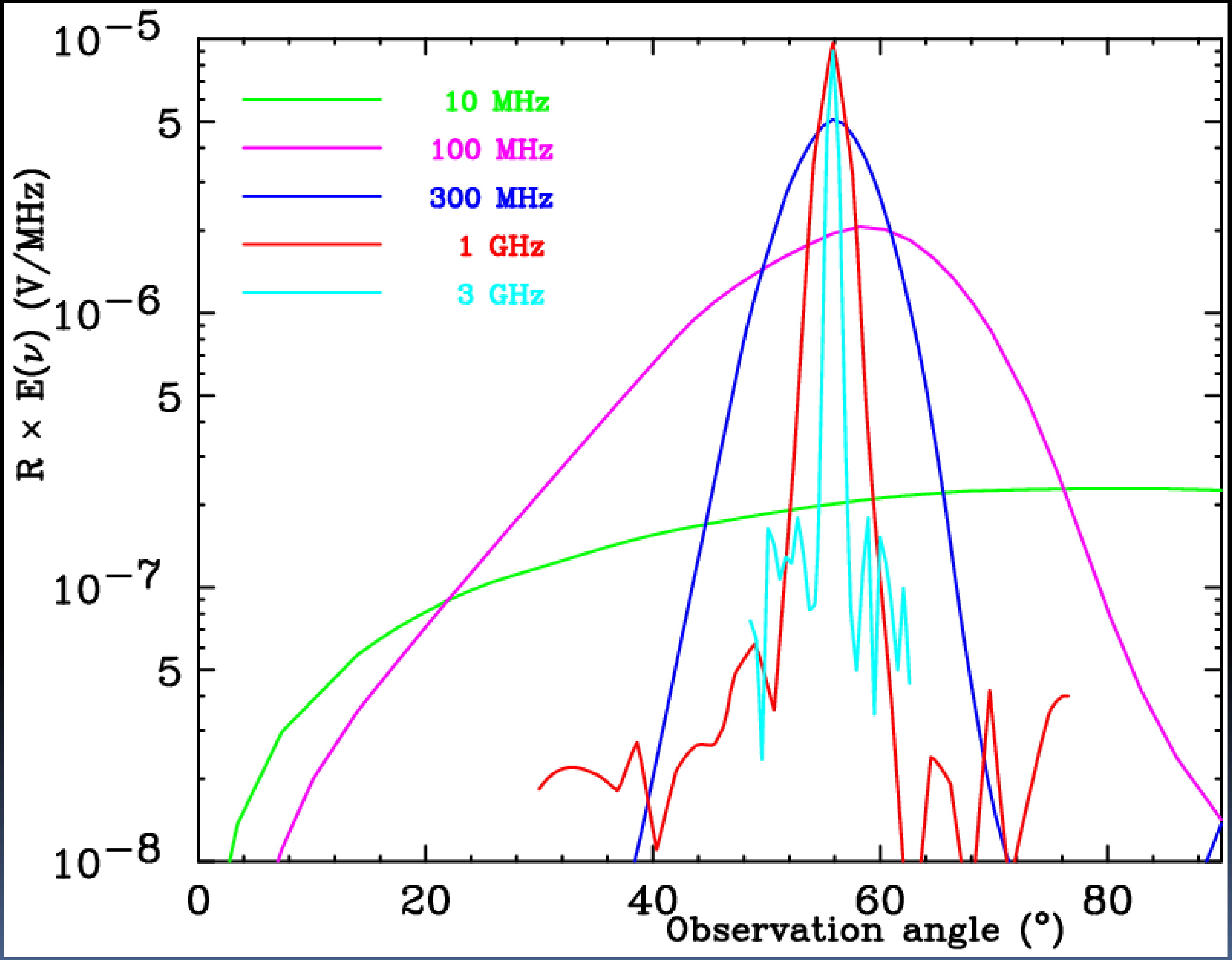
Superposition: simulate shower adding many small tracks



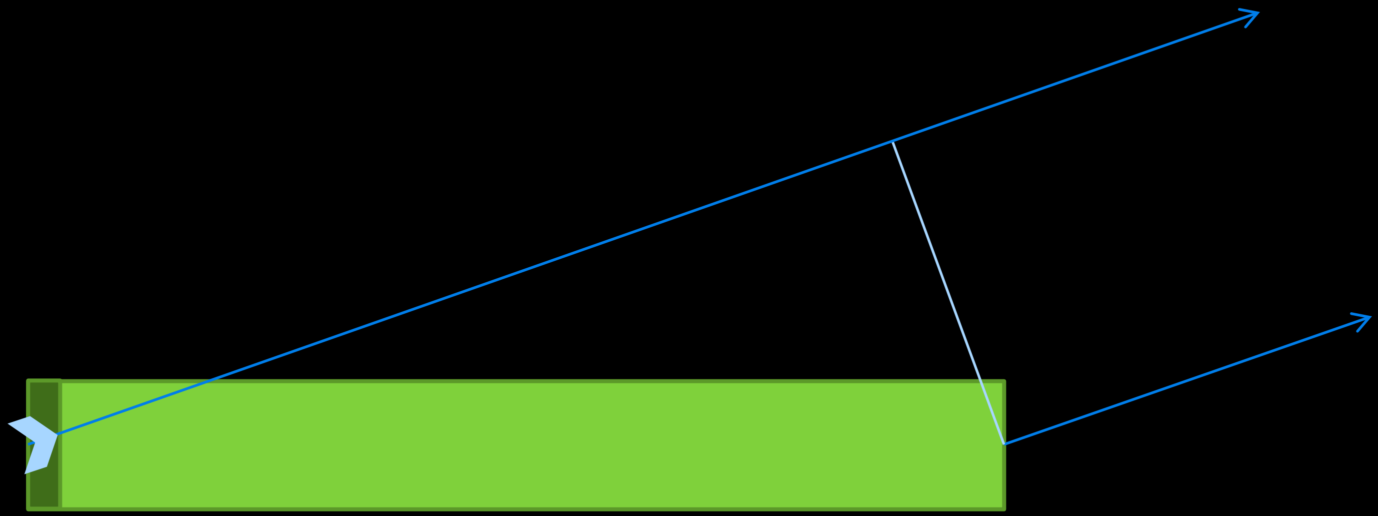
Askary'an effect (dominant in ice)

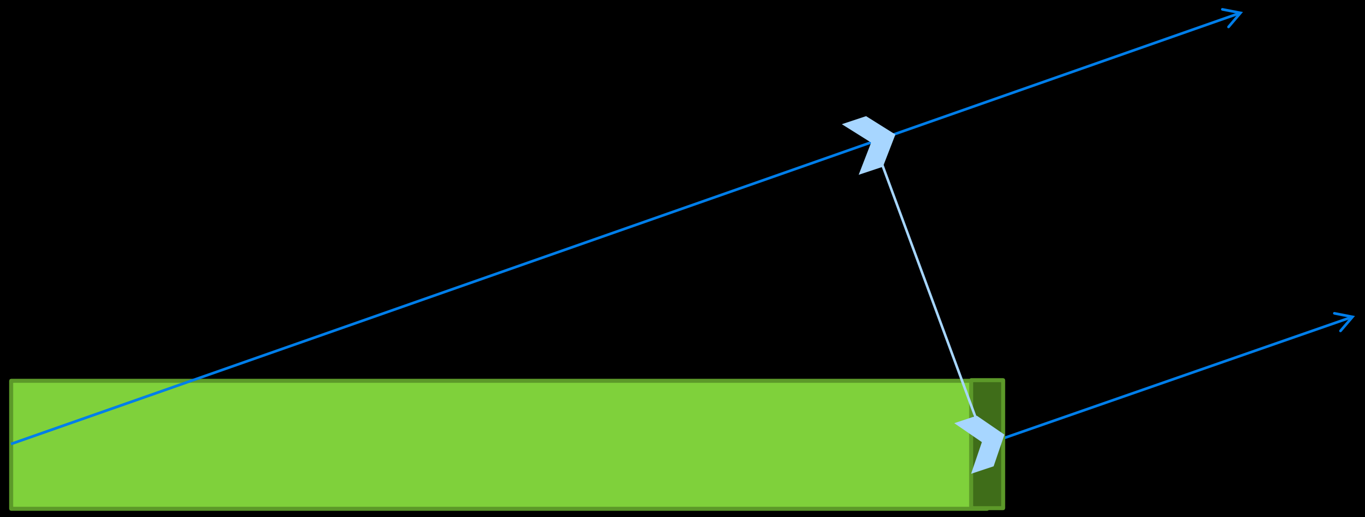


Rich intereference patterns → several scales

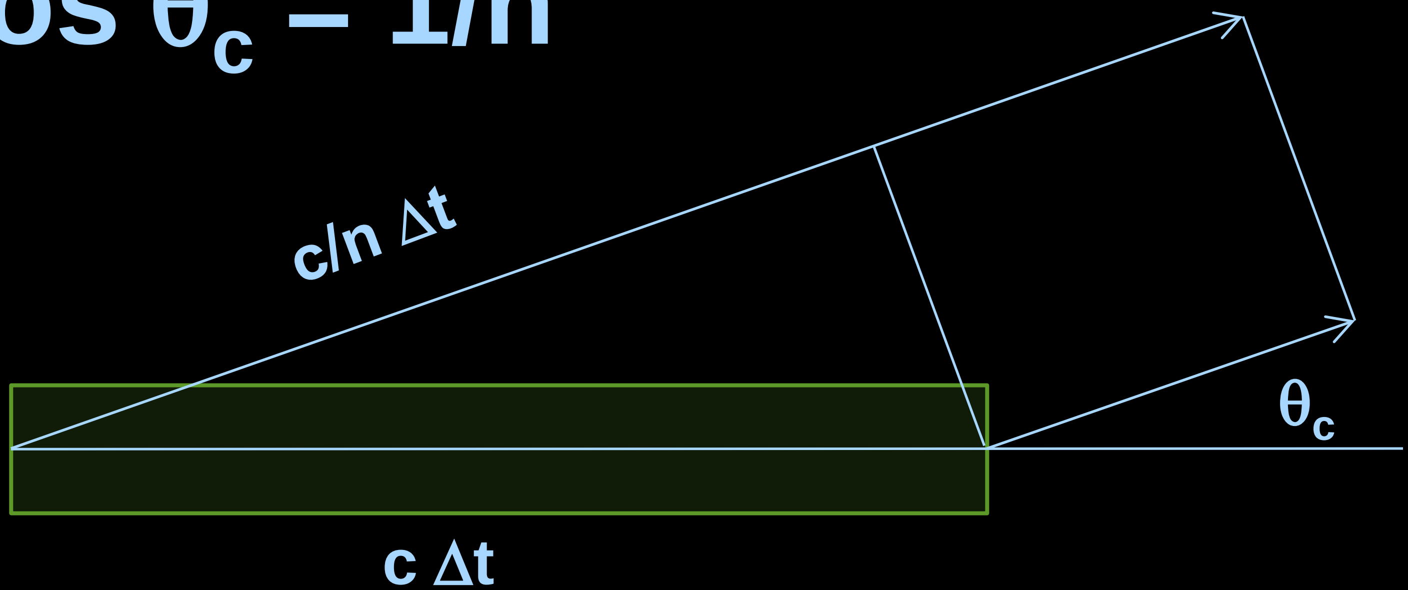


1: length

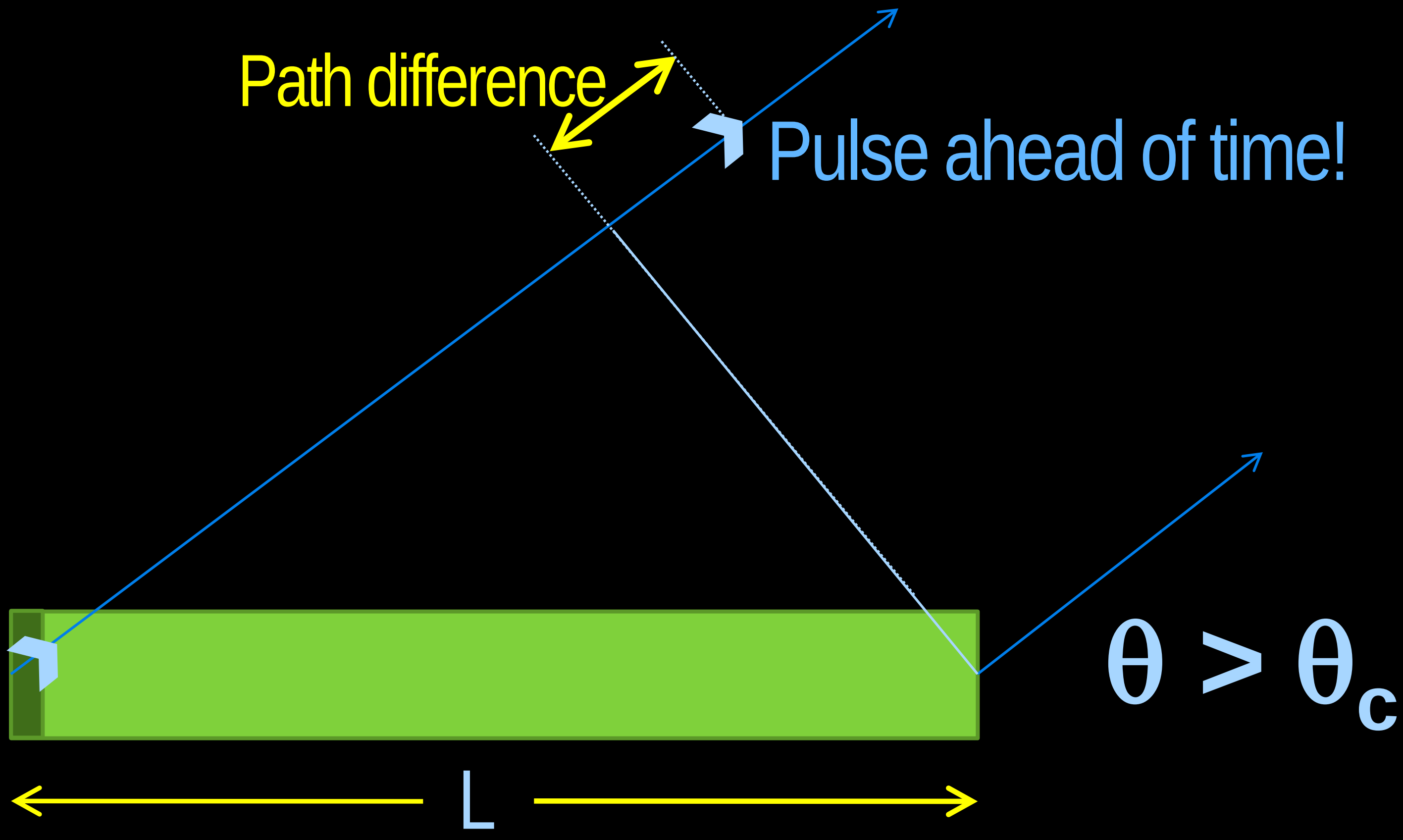




$\cos\theta_c = 1/n$



In Cherenkov direction
the shower front emits in phase at all times



Emission out of phase

path difference $=\lambda$ => diffraction minimum

like in a single slit L ~ slit width

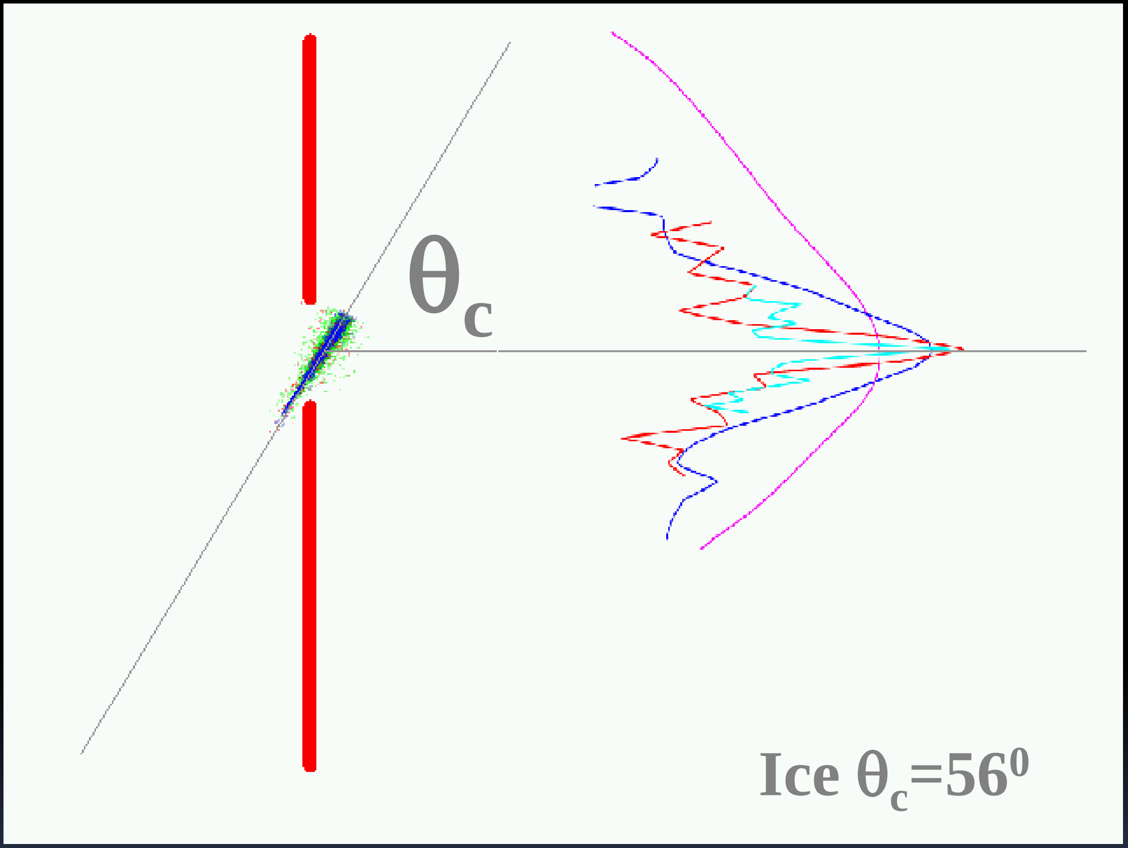
The slit diffraction analogy

If current is "thin":

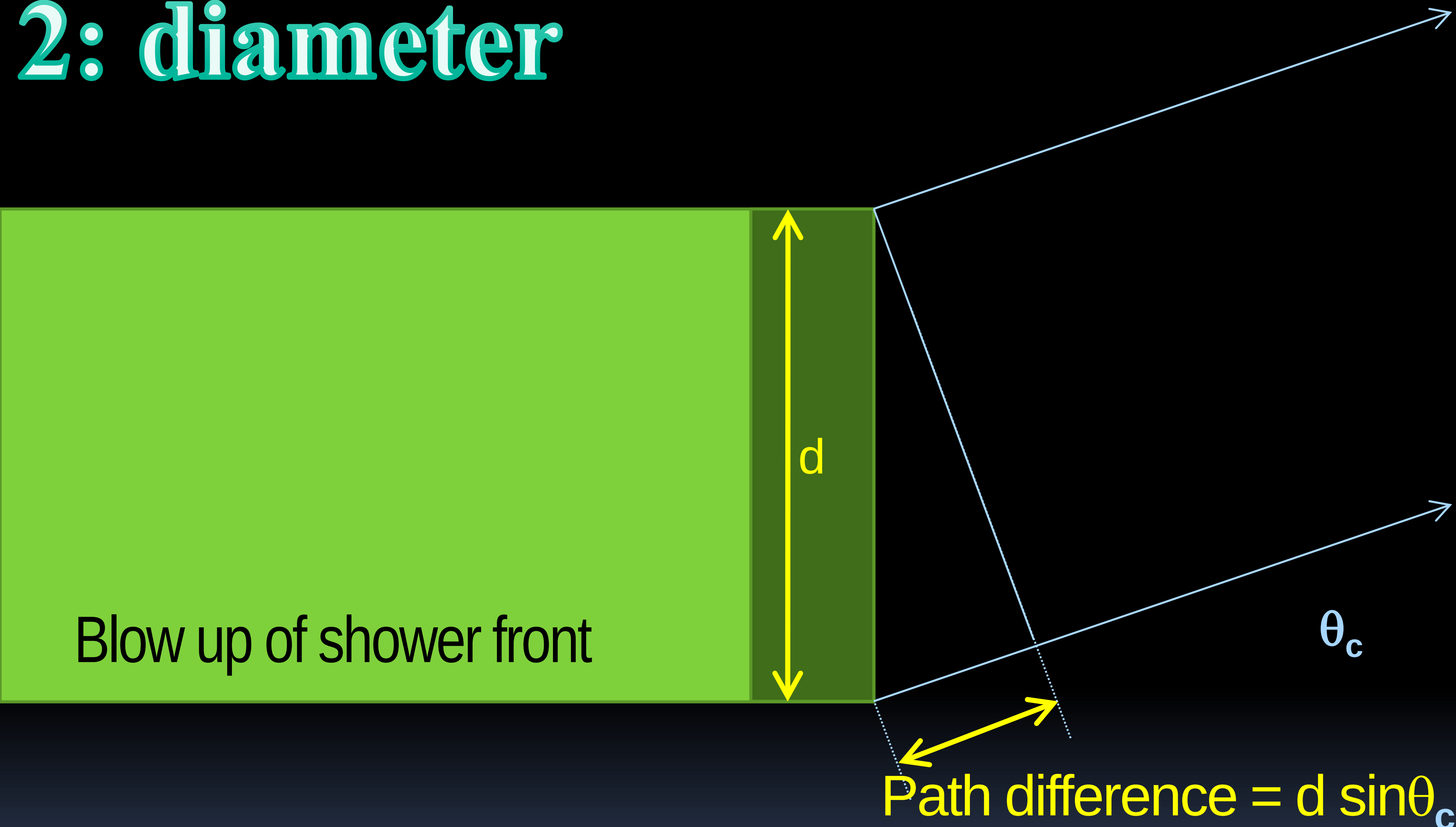
$$\vec{E}(\omega) \propto \frac{i\omega}{R}\int dz Q(z) e^{ikz}$$

Kind of FT with

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

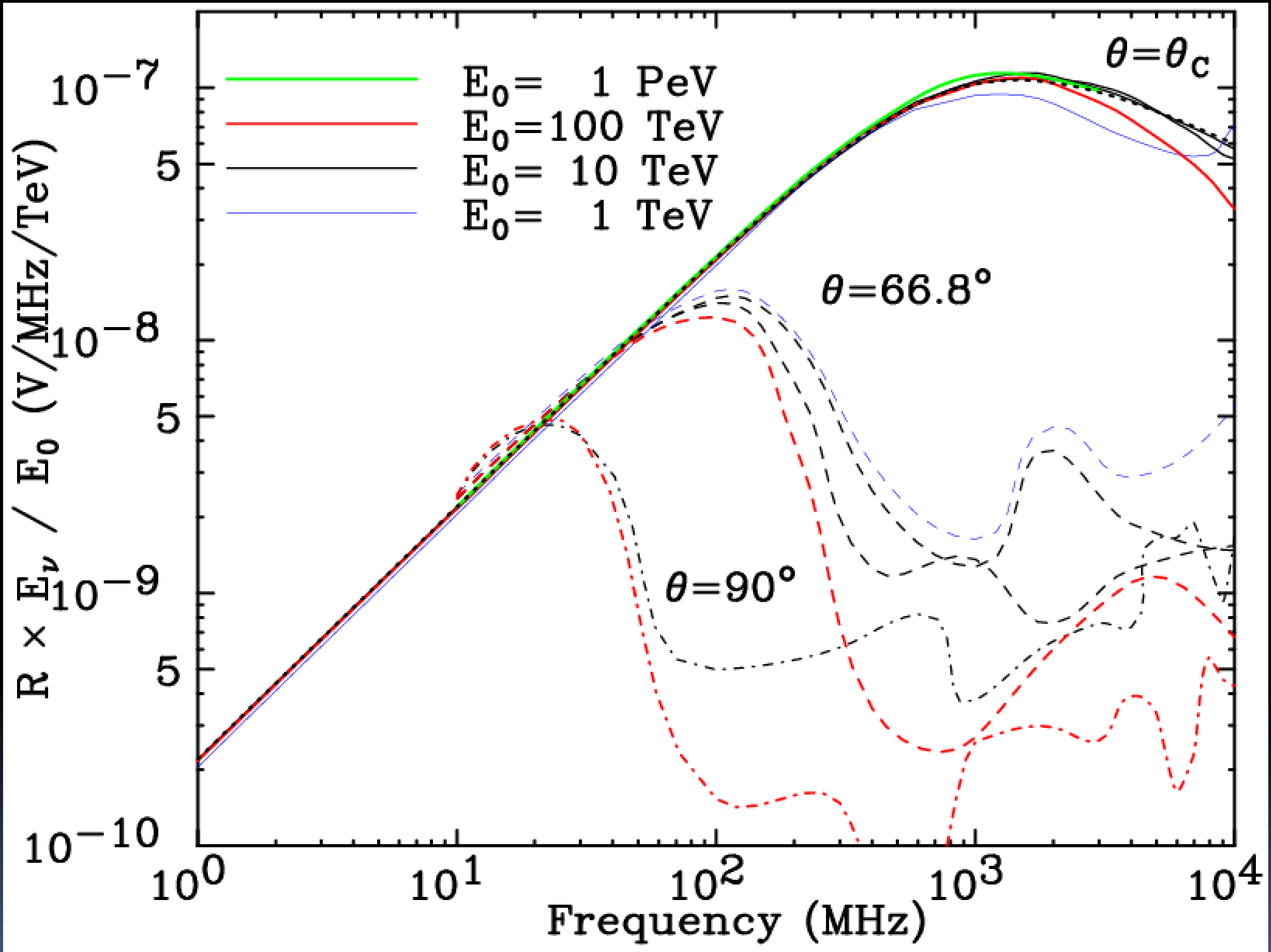


2: diameter



d $\sin\theta_c = \lambda$ => at θ_c

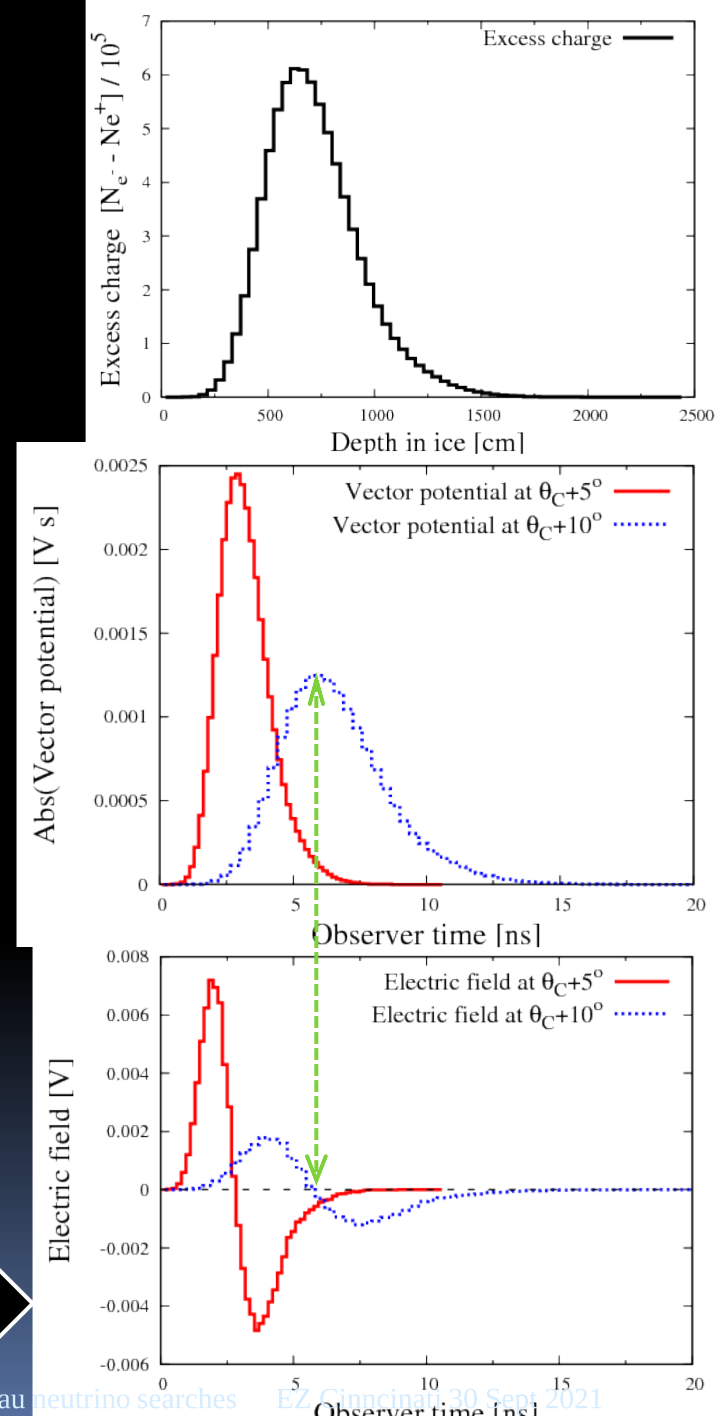
Interference minimum at a lower λ (higher frequency)



E_0= 1 PeV
E_0=100 TeV
E_0= 10 TeV
E_0= 1 TeV
$\theta=\theta_c$
$\theta=66.8°$
$\theta=90°$
10^{-7}
5
10^{-8}
5
10^{-9}
5
10^{-10}
10^0
10^1
10^2
10^3
10^4
Frequency (MHz)
$R \times E_\nu$ / E_0 (V/MHz/TeV)

Unidimensional current
Time domain

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



Vector potential

$$A(t_{obs}, \theta) \approx v\,Q(\zeta)\ /\ (1 - n\beta\cos\theta) / R$$

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

Retardation + time-compression:

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

$$t_{obs} = t_0 \text{ when looked at } \theta_c$$

Electric field

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

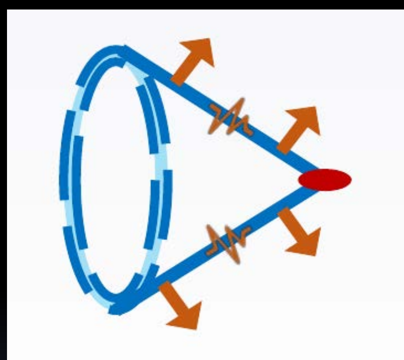
[J. A-M, A. RW, E. Z, PRD **81**, 123009 (2010)]

Electric field:

bi-polar pulses of nano-second time duration at Cherenkov angle

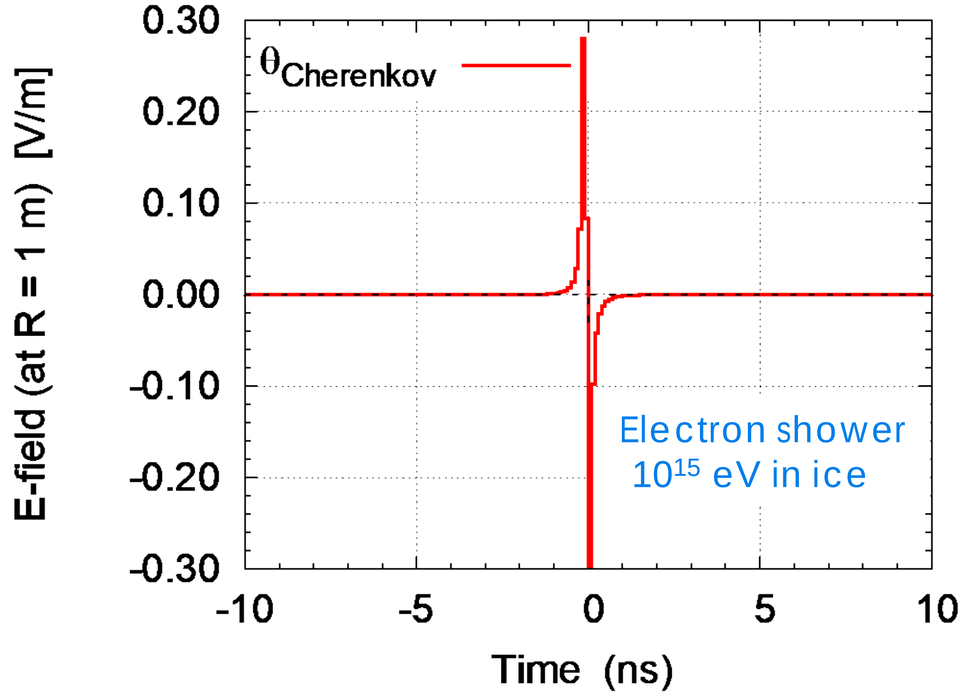
Time duration increases as observer moves away from Cherenkov

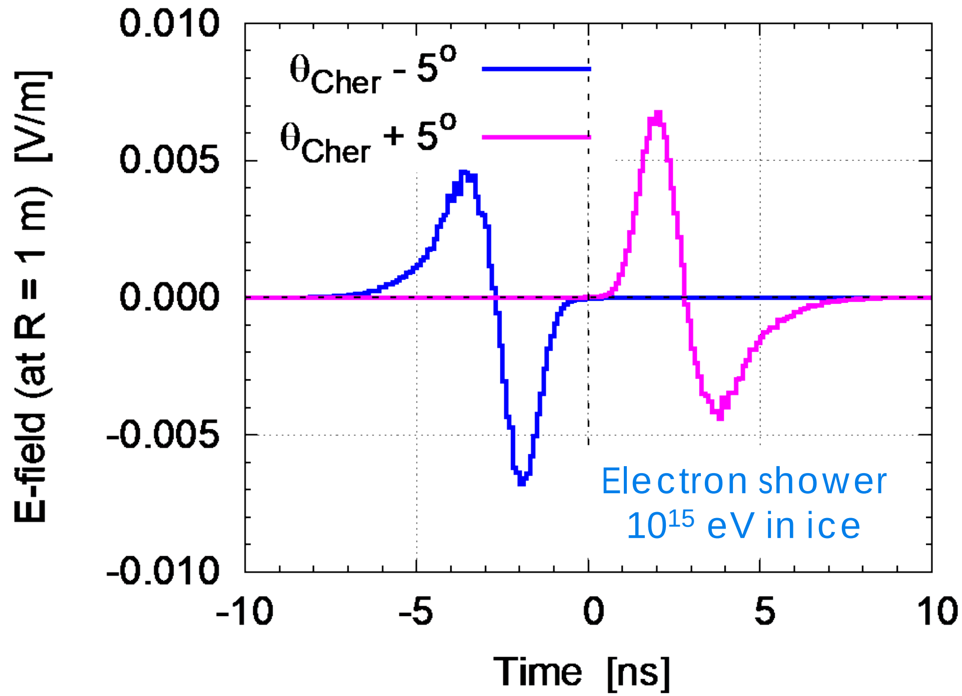
Linearly polarized field



Relativistic effects apparent:

Time reversal inside & outside Cherenkov cone. $f_{\theta+}(t) = -f_{\theta-}(-t)$





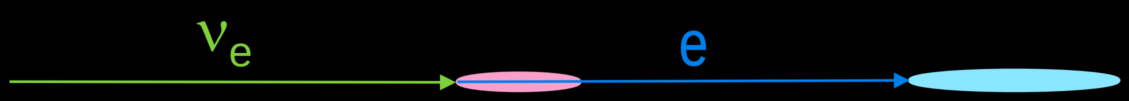
E. Zas, F. Halzen, T. Stanev, PRD 45, 162 (1992)
J. A-M, A. Romero-Wolf, E. Zas, PRD **81**, 123009 (2010)

Coherence: applications for neutrino detection

Shower morfology can help flavor tagging

τ/e showers can separate from hadronic debris

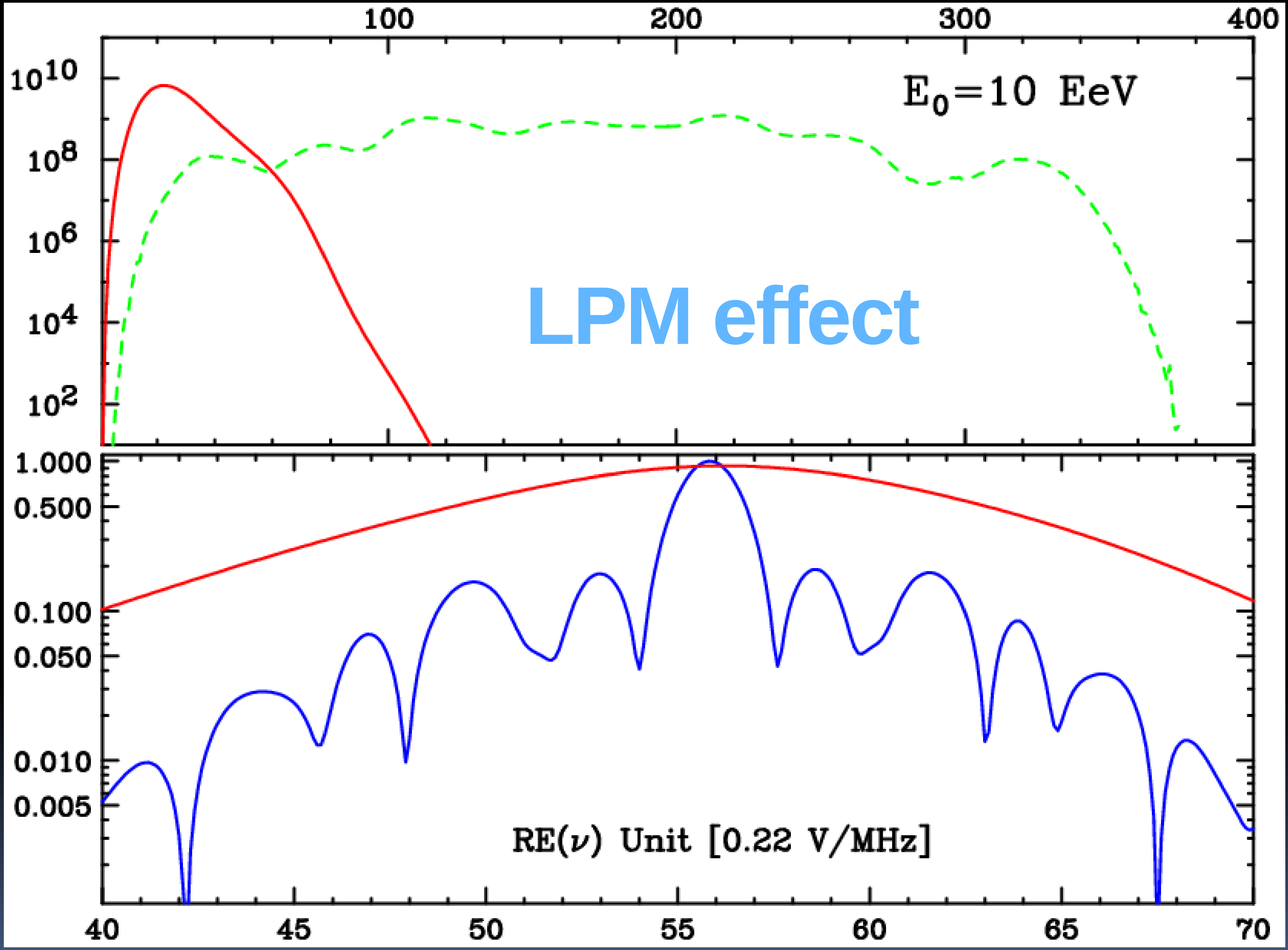
[J. Alvarez-Muñiz et al., PRD 101 (2020) 8, 083005]
[D. García-Fernández et al., PRD 102 (2020) 8, 083011]



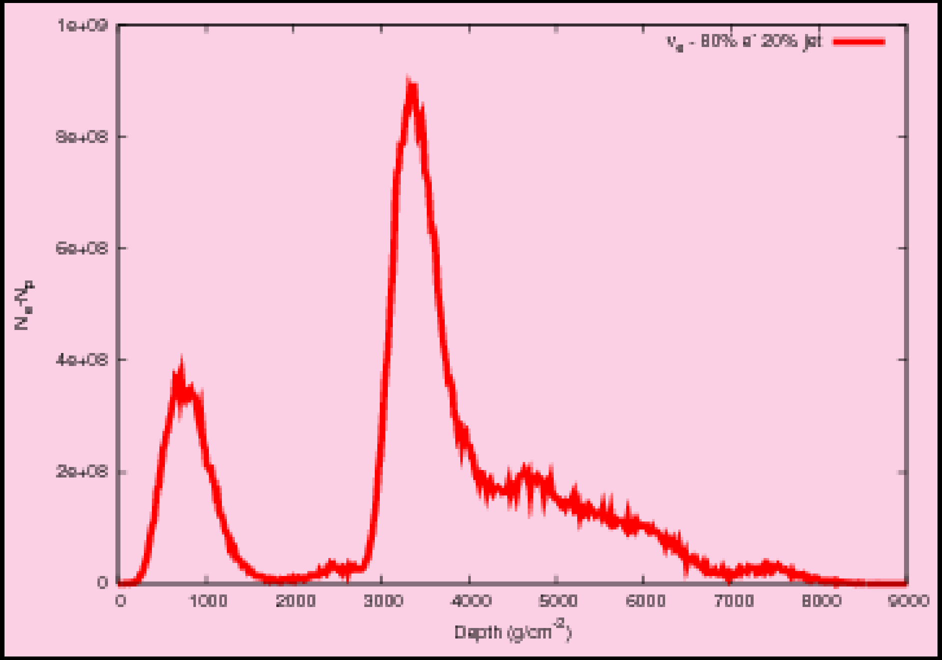
i.e. multiple showers, LPM shower, bremss of μ,τ

It may be possible to measure y, the energy transfer to the nucleus in the colision

[J. Alvarez-Muñiz, EZ., PRD 61 (2000) 12, 123003]]

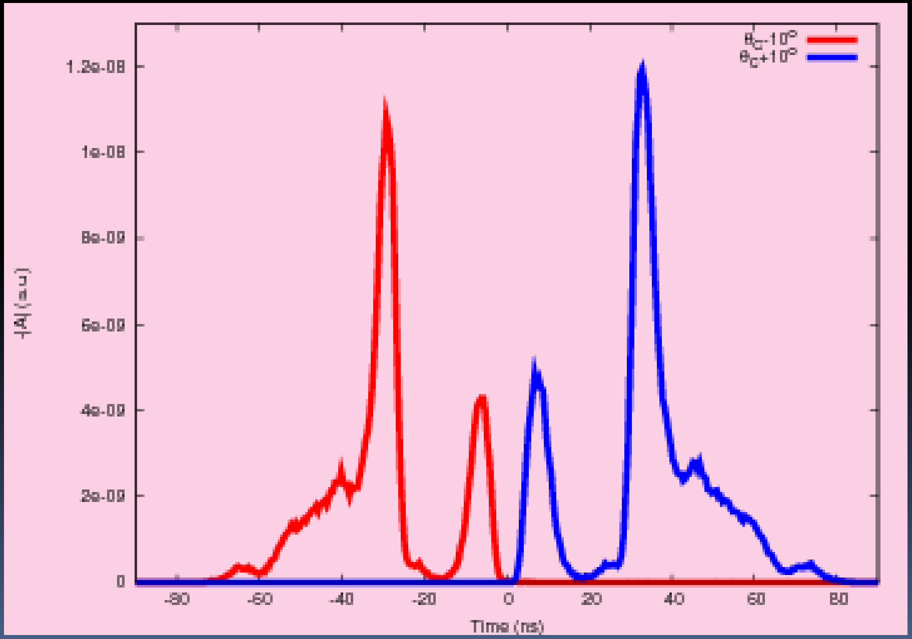


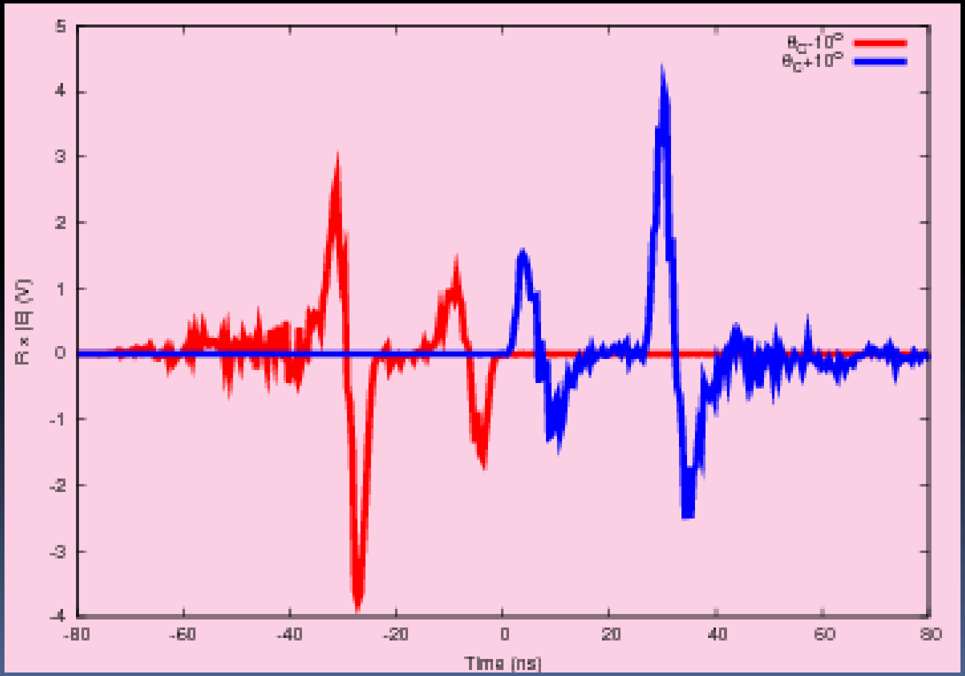
100
200
300
400
10^{10}
10^8
10^6
10^4
10^2
E_0=10 EeV
LPM effect
1.000
0.500
0.100
0.050
0.010
0.005
RE(ν) Unit [0.22 V/MHz]
40
45
50
55
60
65
70



$\nu_e + N \rightarrow e + jet$

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

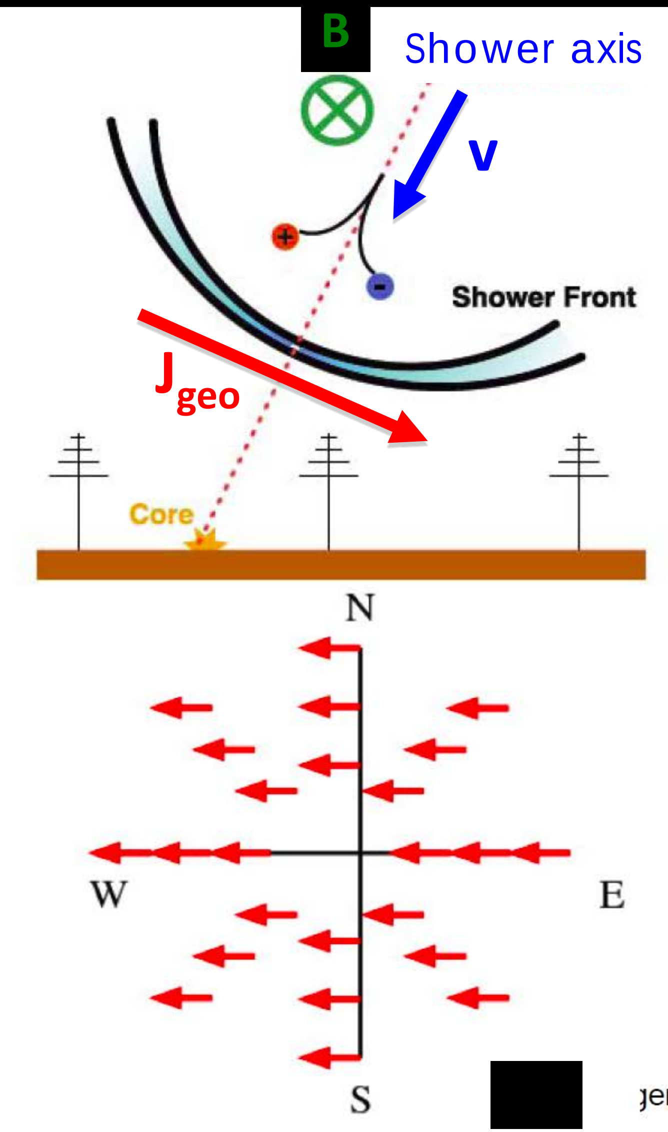




Why is the atmosphere different?

B field develops larger transverse currents

Geomagnetic effect

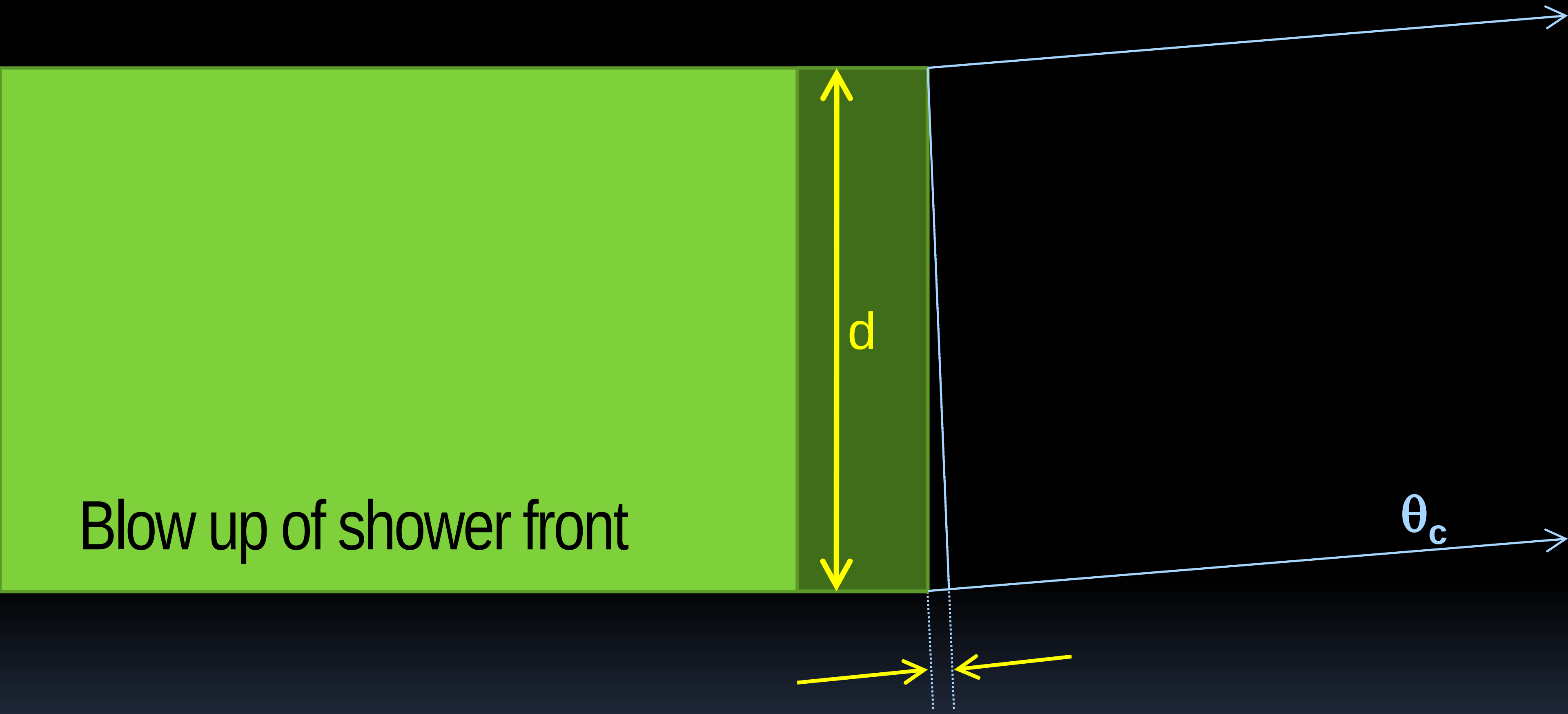


Proportional to number of e^- and e^+
Different polarization **v** x **B**
Showers ~1000 x larger (wrt ice) =>MHz
Cherenkov angle is very small 0.4 1.2 deg

New complex issues
Excess charge Geomagnetic interference
There is a varying refractive index
There is curvature of the atmosphere
…

ANITA: GHz from CR (unexpected)

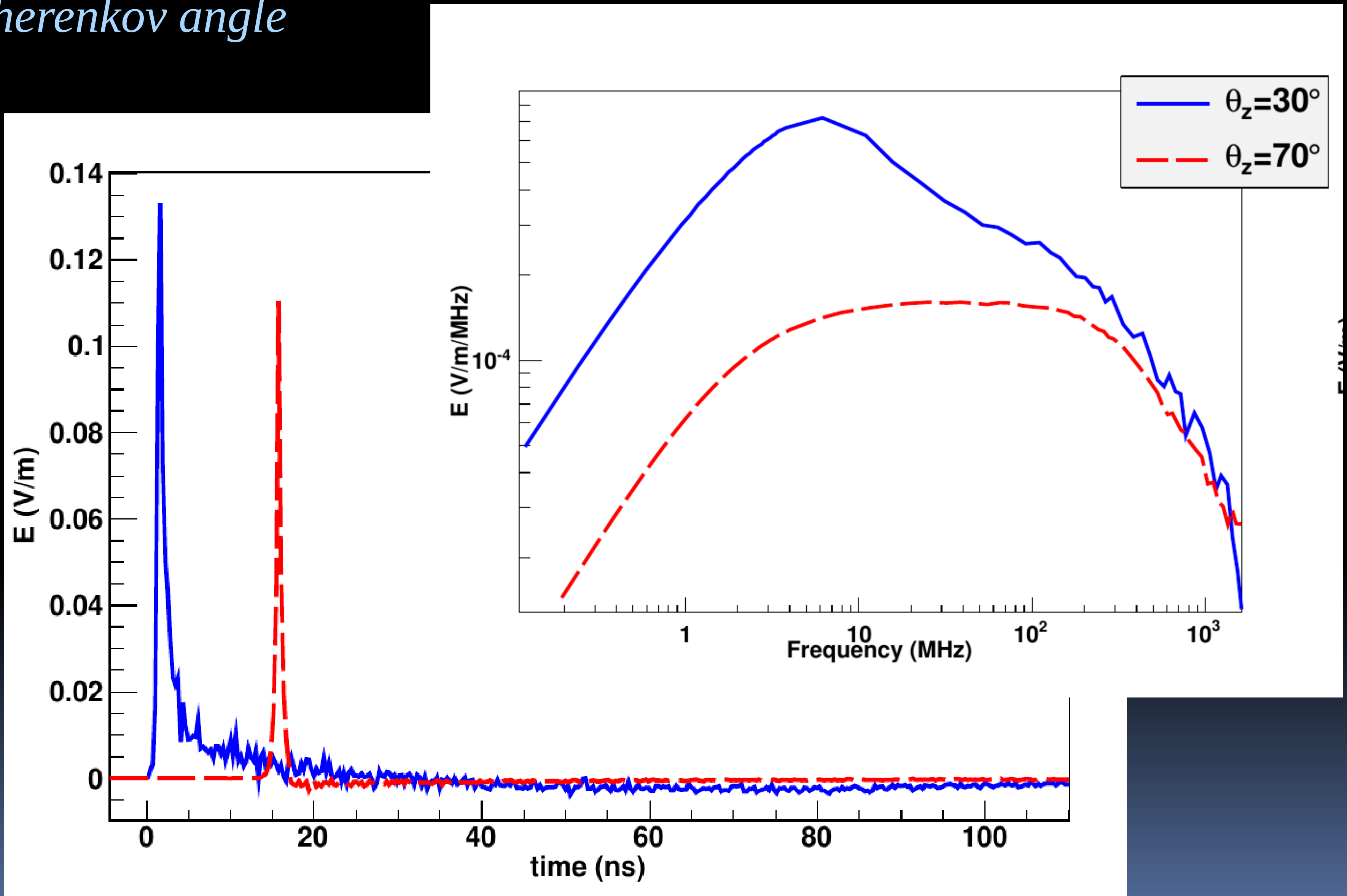
Diameter 1000 times larger BUT θ_c VERY small



Path difference = d $\sin\theta_c$

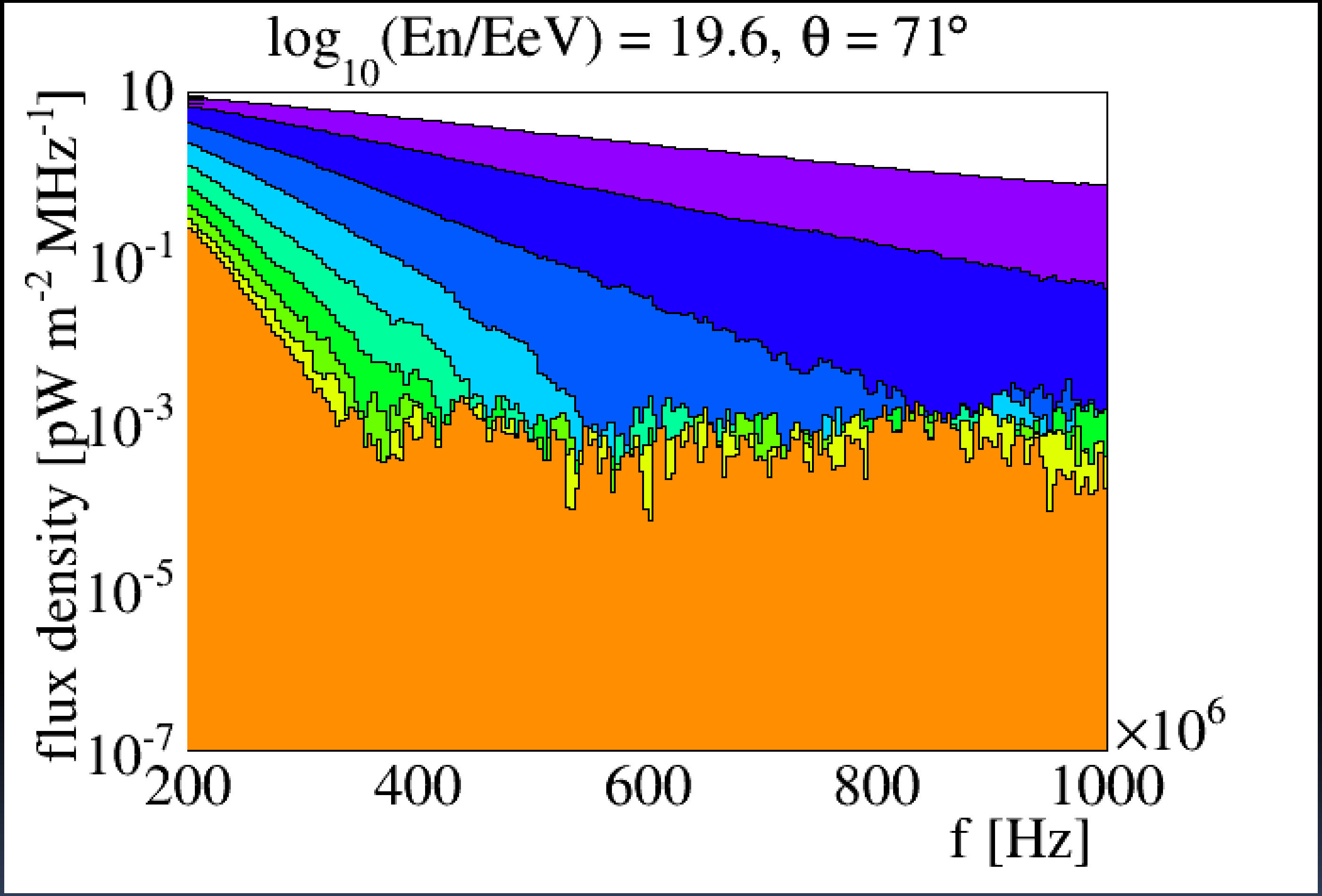
At θ_c some coherence up to the GHz in spite of scale factor!!

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



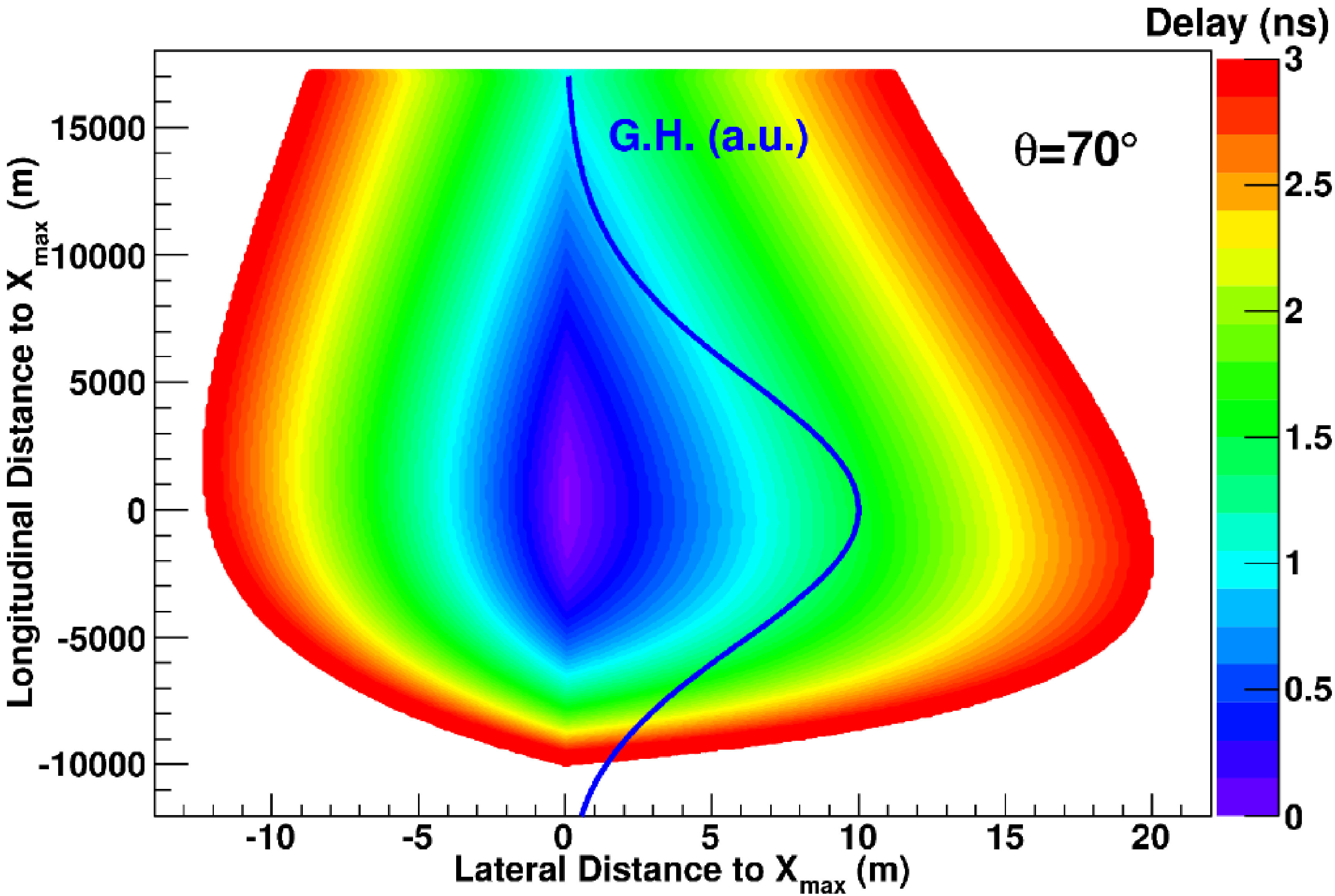
Different spectra as we get away from Cher angle

Inner cone



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

Blow up of central region



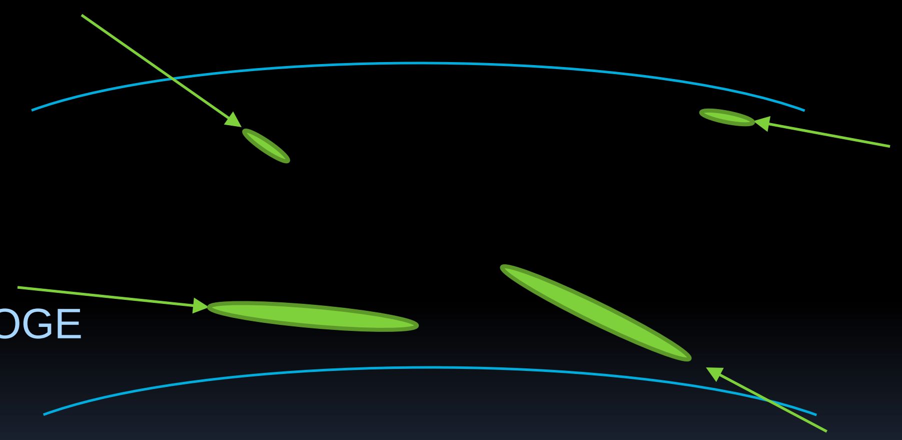
A guide through proposals and experiments

Optical (fluorescence/Cherenkov):

- Dense
  - Ice IceCube
  - Water ANTARES
- Air (showers)
  - From satellite POEMMA
  - From balloon EUSO-SPB
  - From mountain TRINITY

Radio:

- Dense ICE
  - From within ARA
  - From surface ARIANNA
  - From above ANITA
- Air
  - From balloon ANITA
  - From mountain BEACON, TAROGE
  - From ground GRAND
- Moon
  - From Earth NuMoon

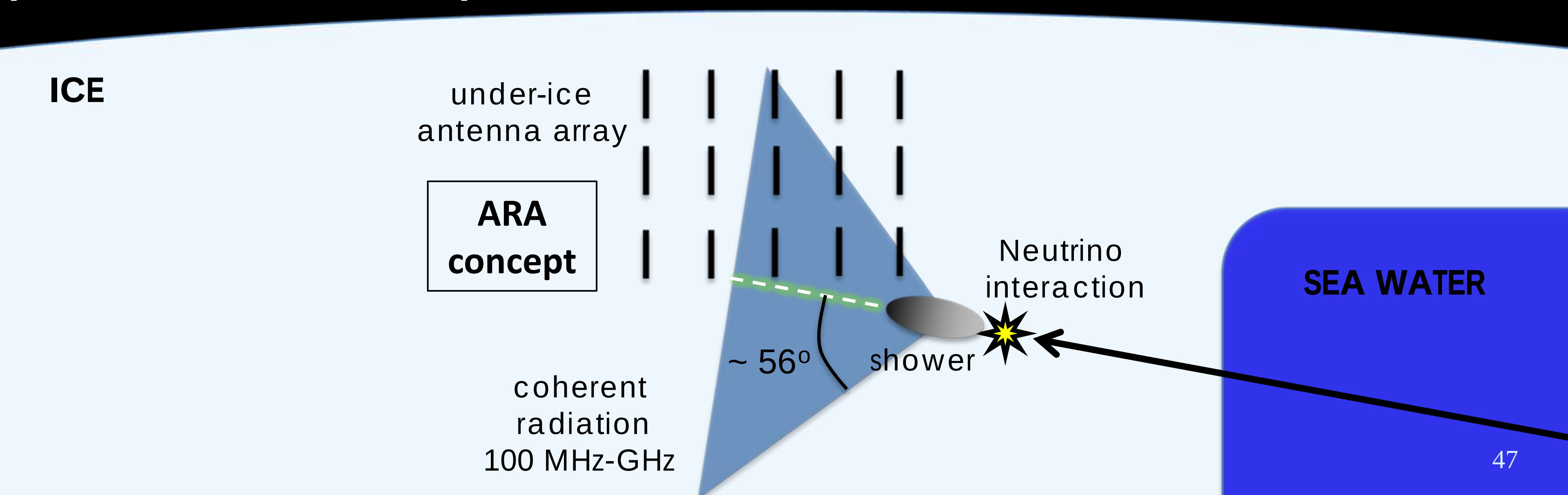


Particles:

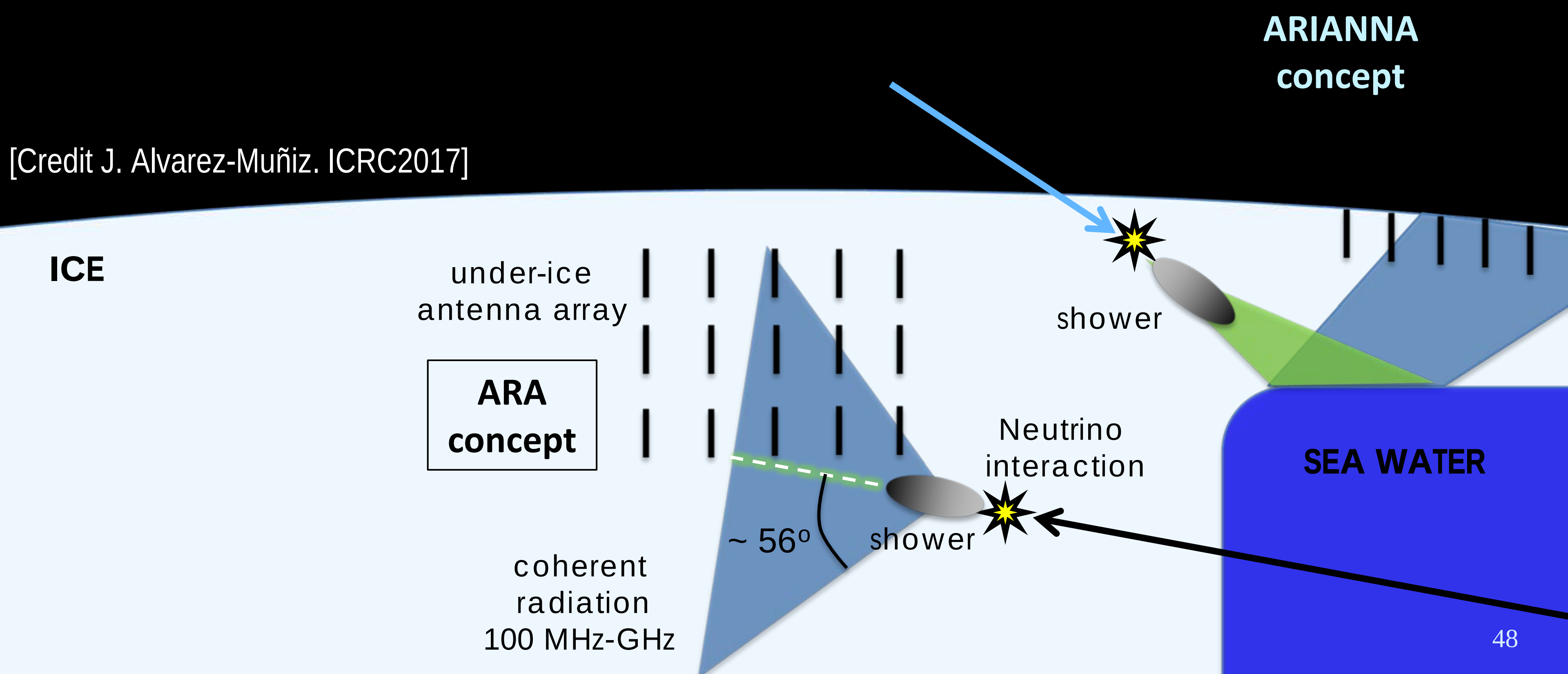
- Air
  - Regular Pierre Auger Observatory, TA
  - V-Valley TAMBO

The radio technique in dense media

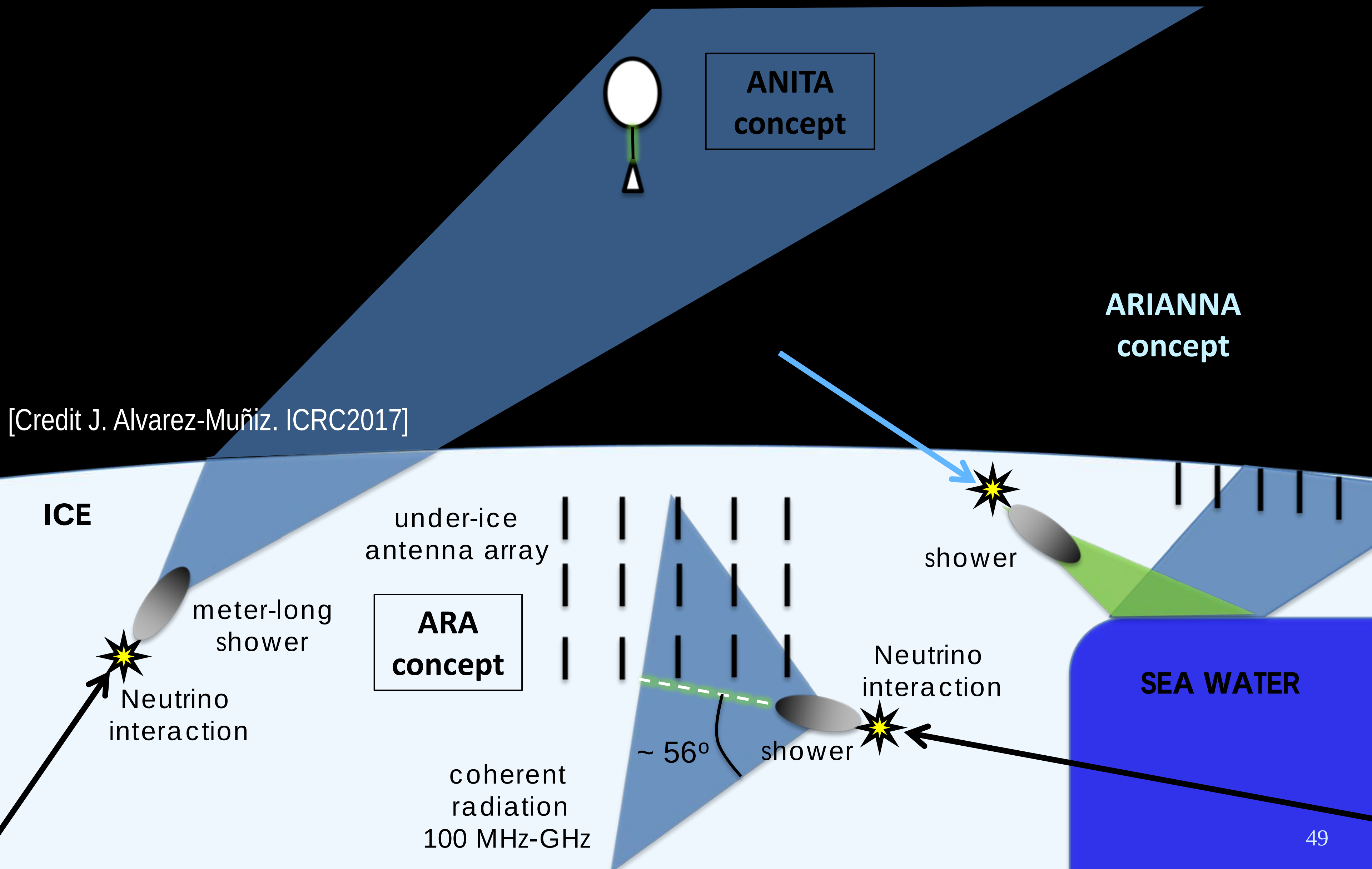
[Credit J. Alvarez-Muñiz. ICRC2017]



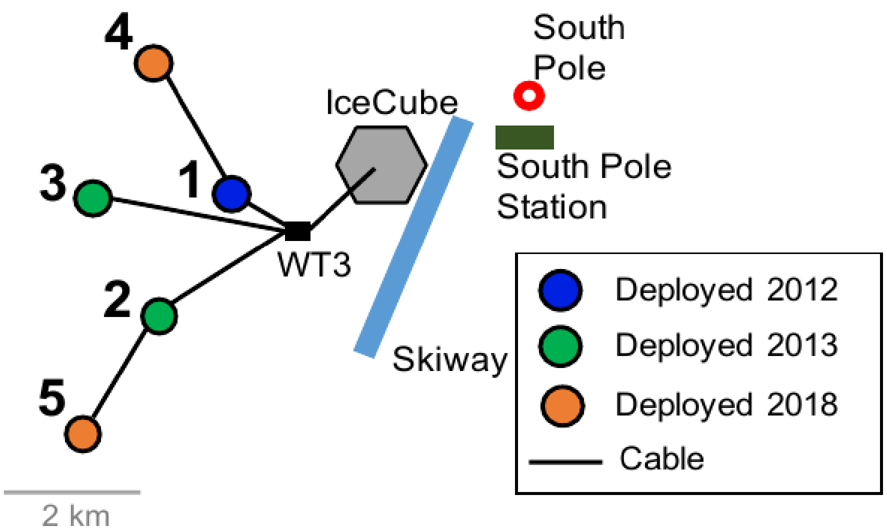
The radio technique in dense media

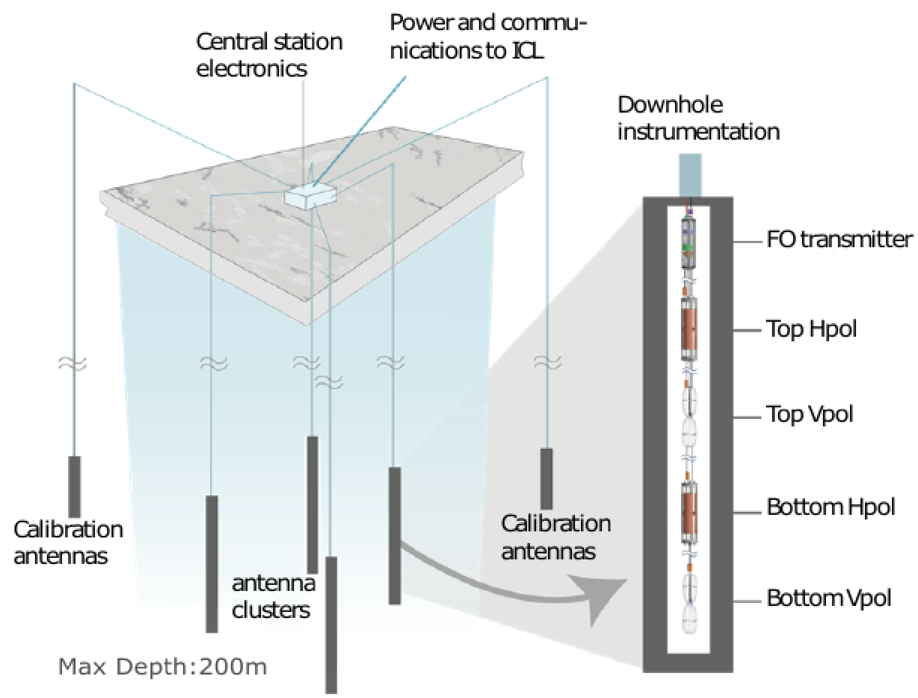


The radio technique in dense media



ARA: Askary’an Radio Array

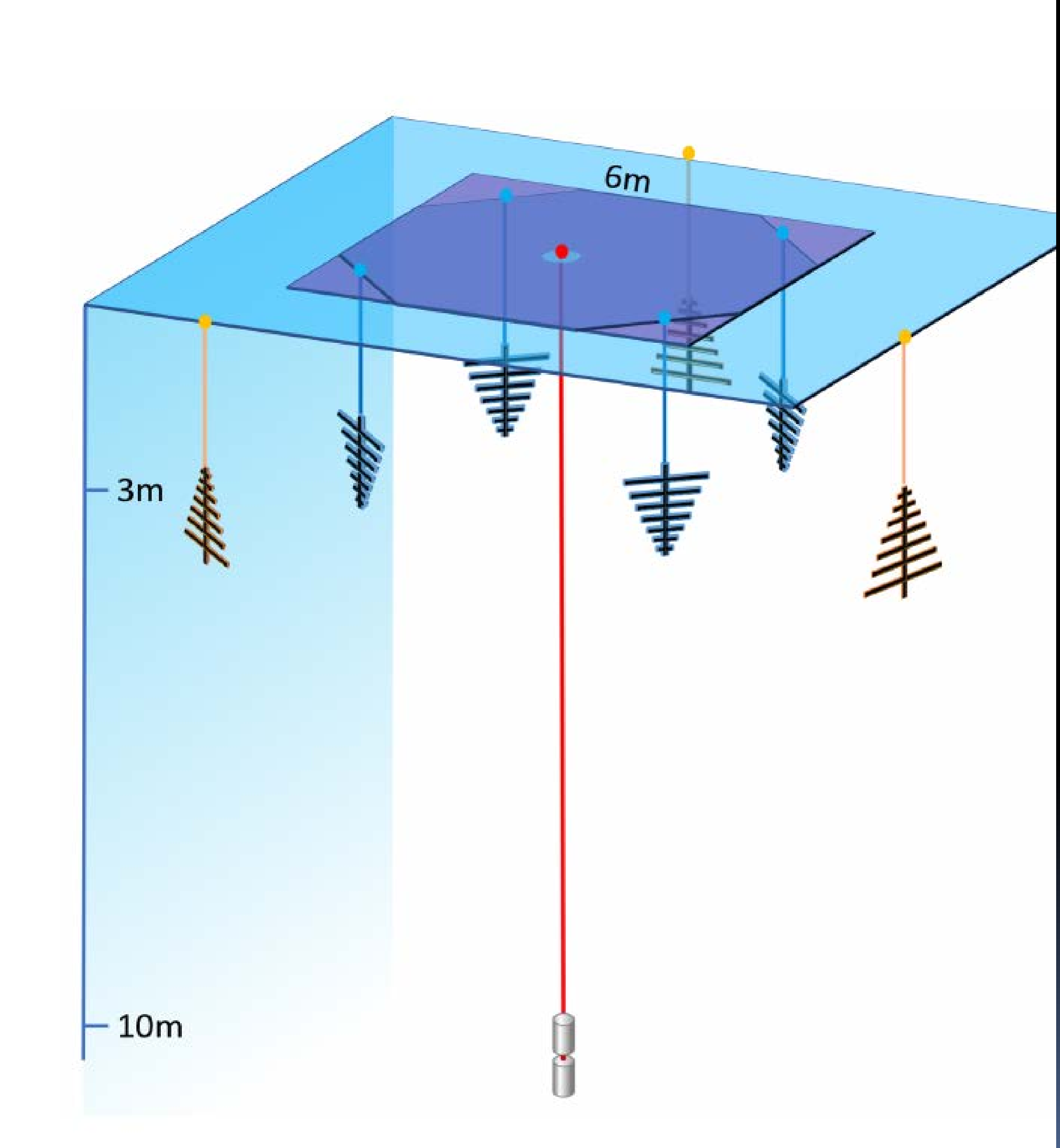




[P. Allison et al. PRD 102 (2020) 043021]

Since 2010
5 stations
Deep holes
Demonstrated trigger with phased array
Limits obtained

ARIANNA



Since 2010
LPDA at surface
Located on Ross shelf
Larger FoV
CR sensitive (veto)
CR showers seen
R interf removed!

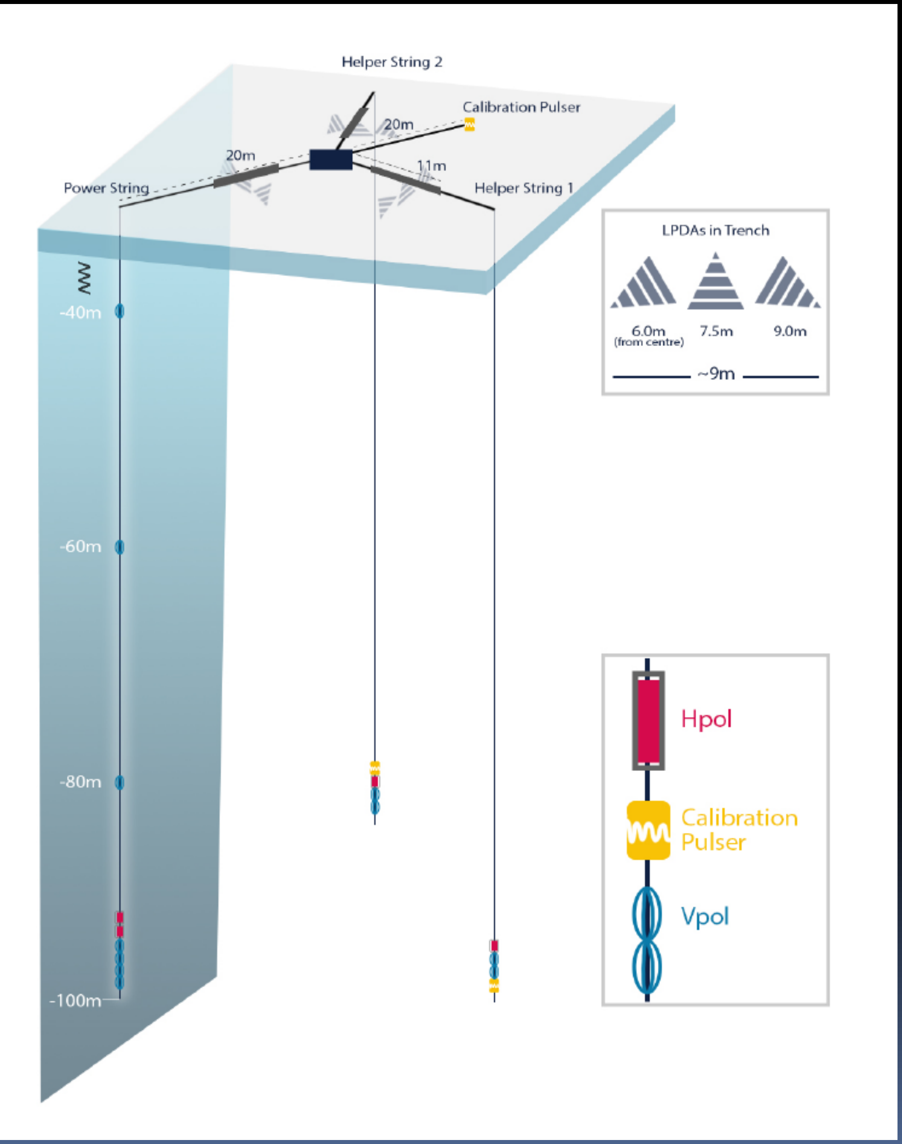
Next step: ARIANNA 200
200 stations

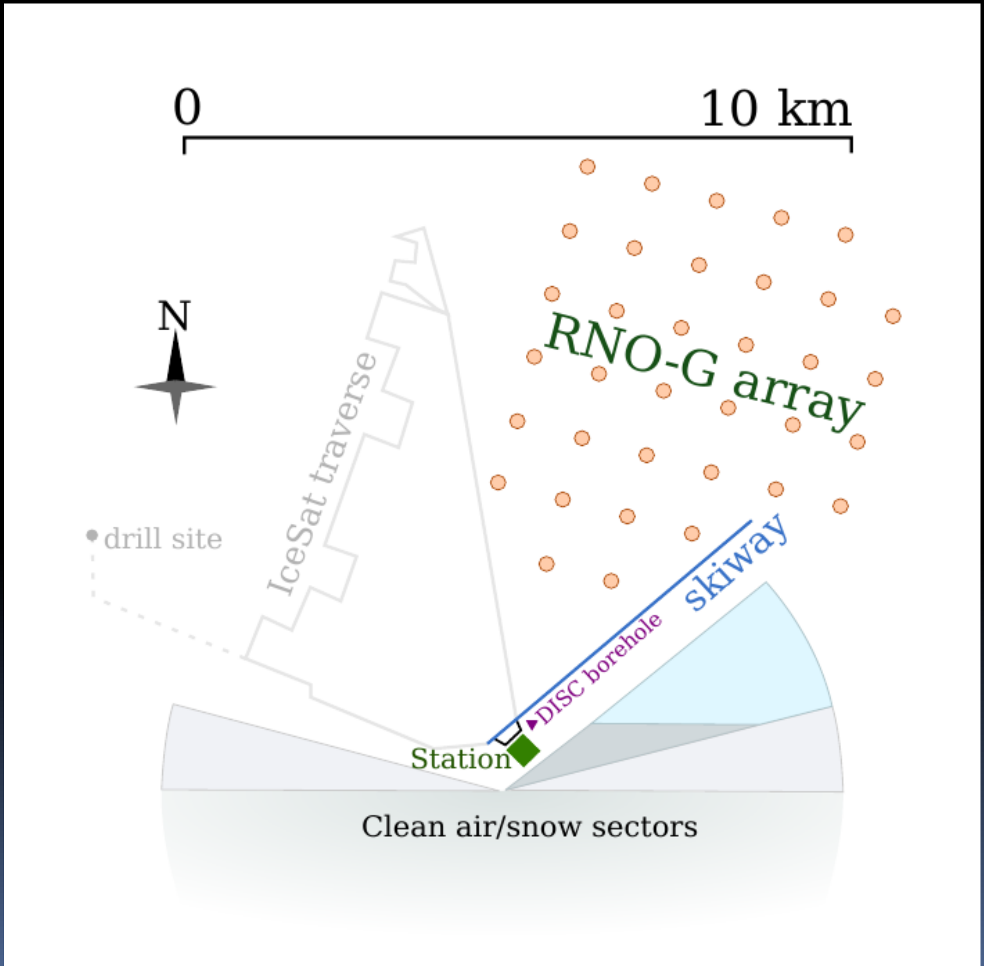
[S. Barwick Proc. ICRC21 (2021)]

RNO-G

2021-2024
deployment started in Greenland
- 50 km^2 35 phased array stations
- Surface and 100m deep

[J.A. Aguilar et al. JINST 16 (2021) 03 P03025]



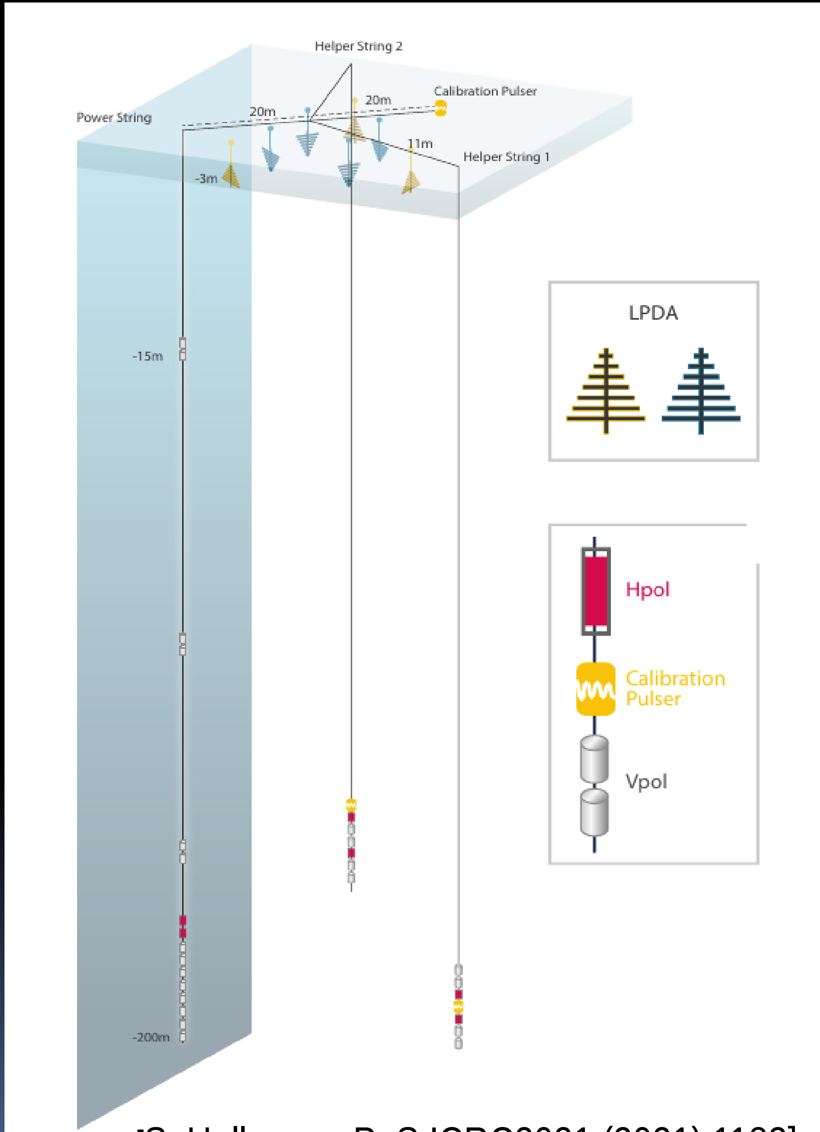


IceCube Gen2 Radio

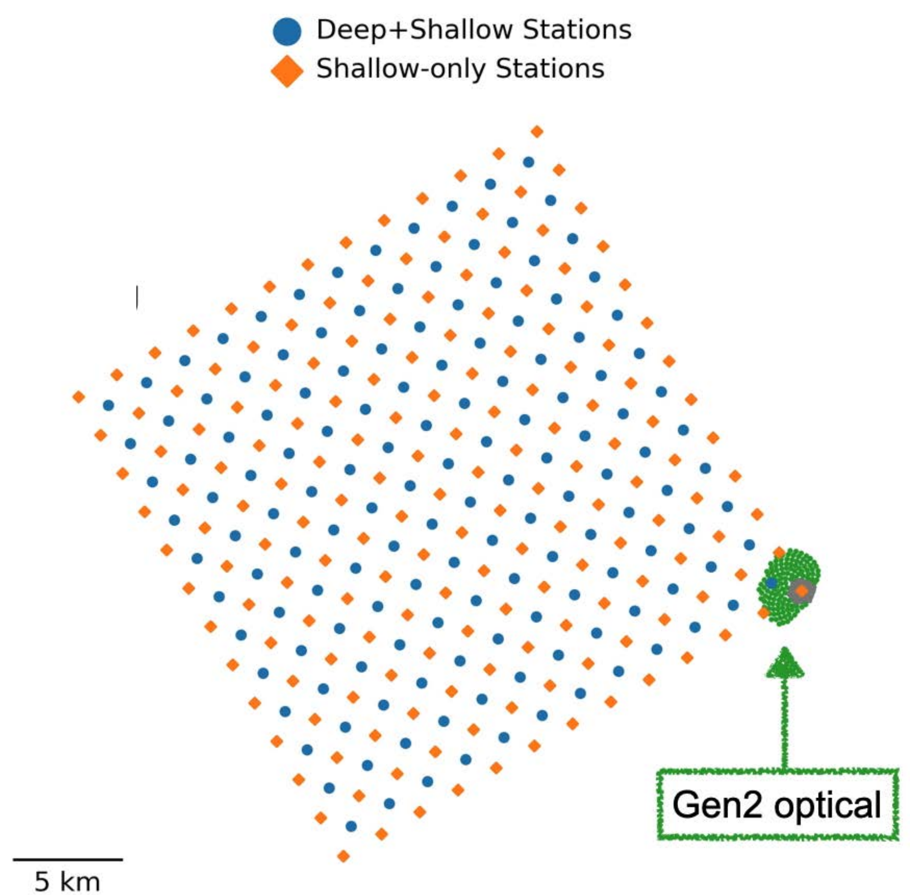
500 km^2 2027?

Builds on from progress

- Phased stations
- Surface + deep
- CR sensitive (veto)



[S. Hallmann, PoS ICRC2021 (2021) 1183]



ANITA: ANtarctic Impulsive Transient Antenna

Since 2004 much experience!!

Four flights, I, II, III, IV

~1 month

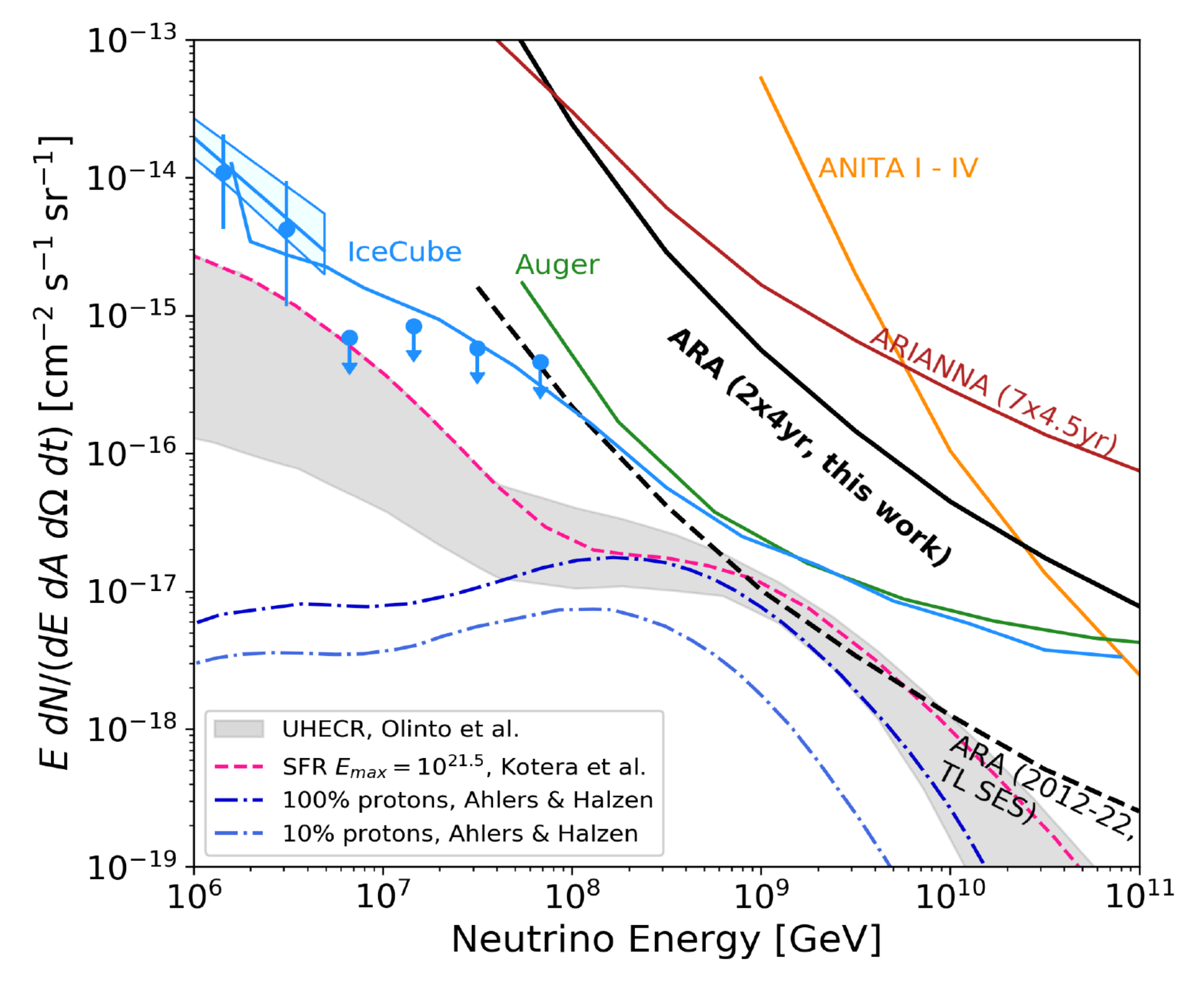
Many results

- limits: (best > 30 EeV)
  - Look for ice showers (Askary'an)
- CR measured (air showers)
- Intriguing events in flights I, III, IV

[P.W. Gorham et al., Astrp. Phys. 32 (2009) 10]

Existing diffuse bounds

Radio → >EeV
Anita > 30 EeV



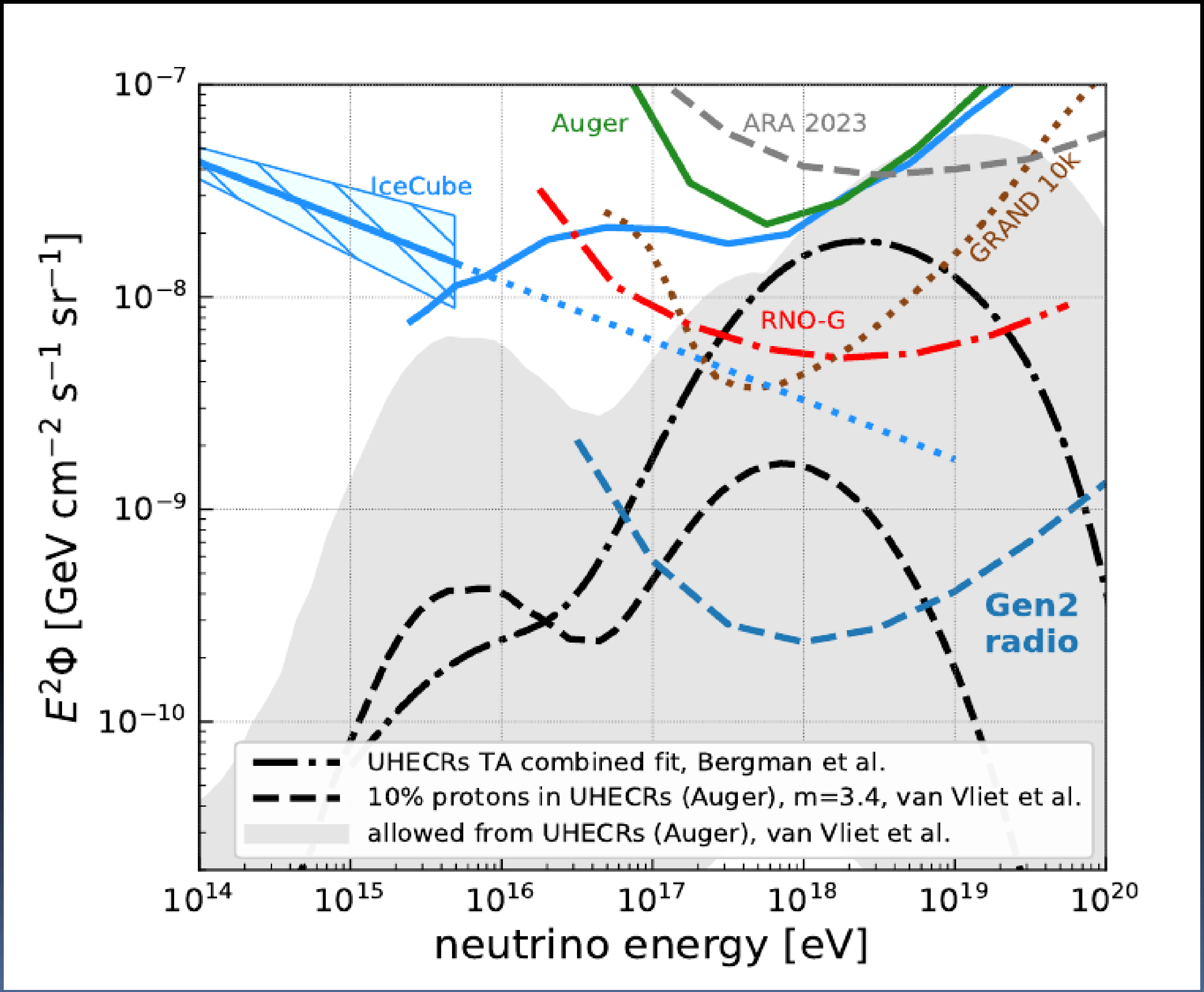
Projected diffuse bounds (10 years)

RNO-G
ARIANNA 200

Extrapolation of IceCube data

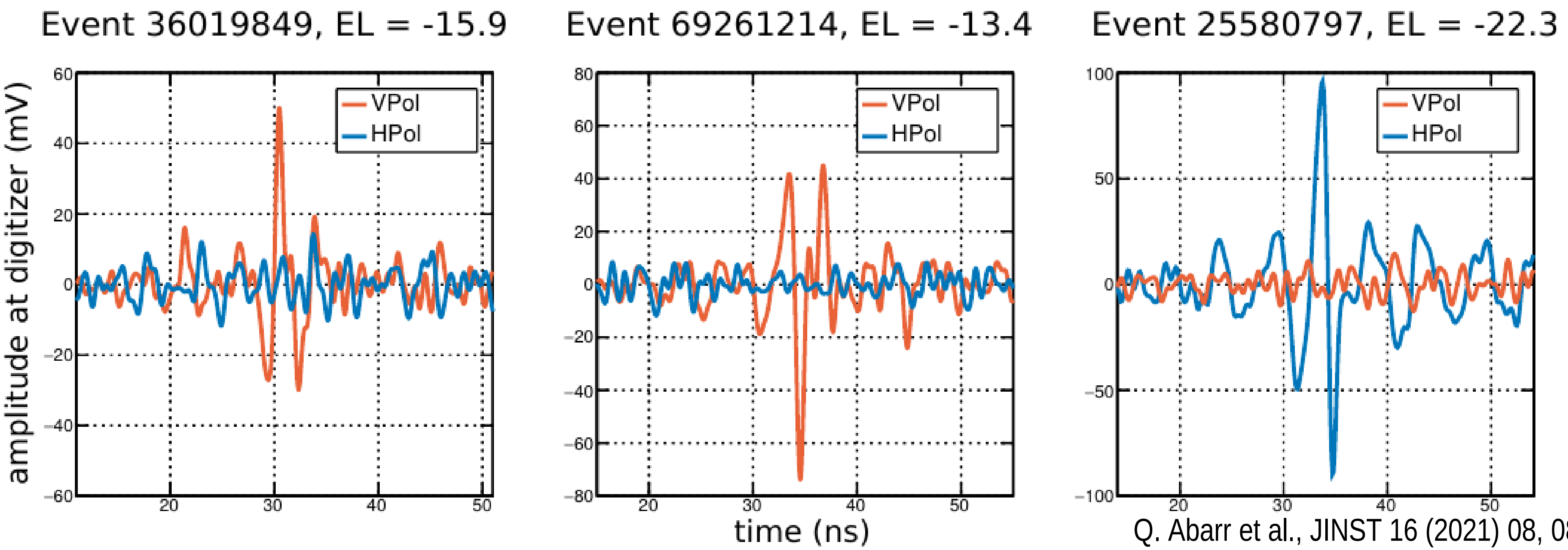
IceCube-Gen2

Cosmological neutrinos



ANITA:
Mistery events

Pulses from ice should be identified by Vertical polarization



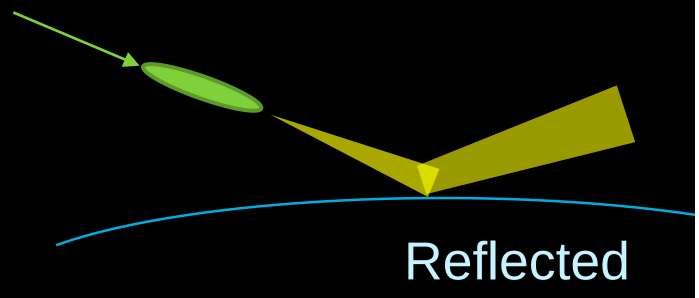
Q. Abarr et al., JINST 16 (2021) 08, 08]

vertically-polarized candidates in 2 analyses

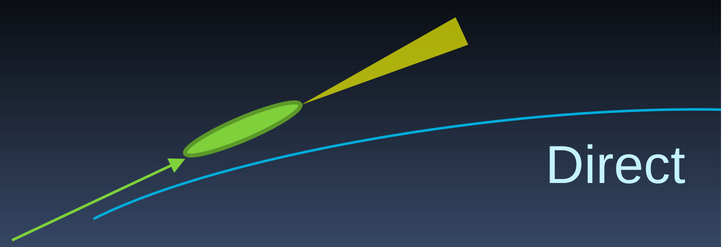
CR candidate

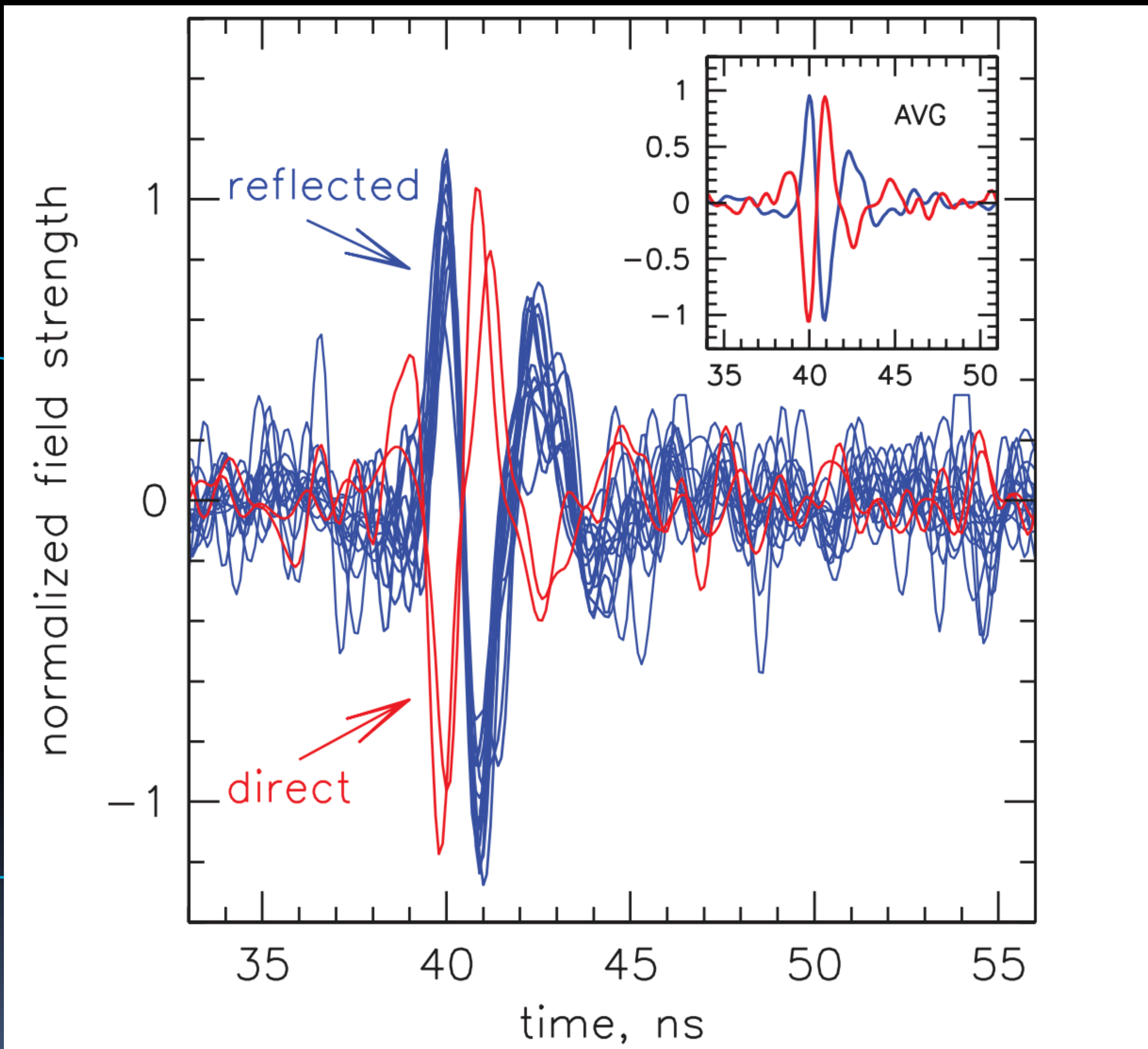
[P.W. Gorham et al., PRD 99 (2019) 12, 12001]

Horizontal polarization consistent with air showers



Separation by polarity inversion

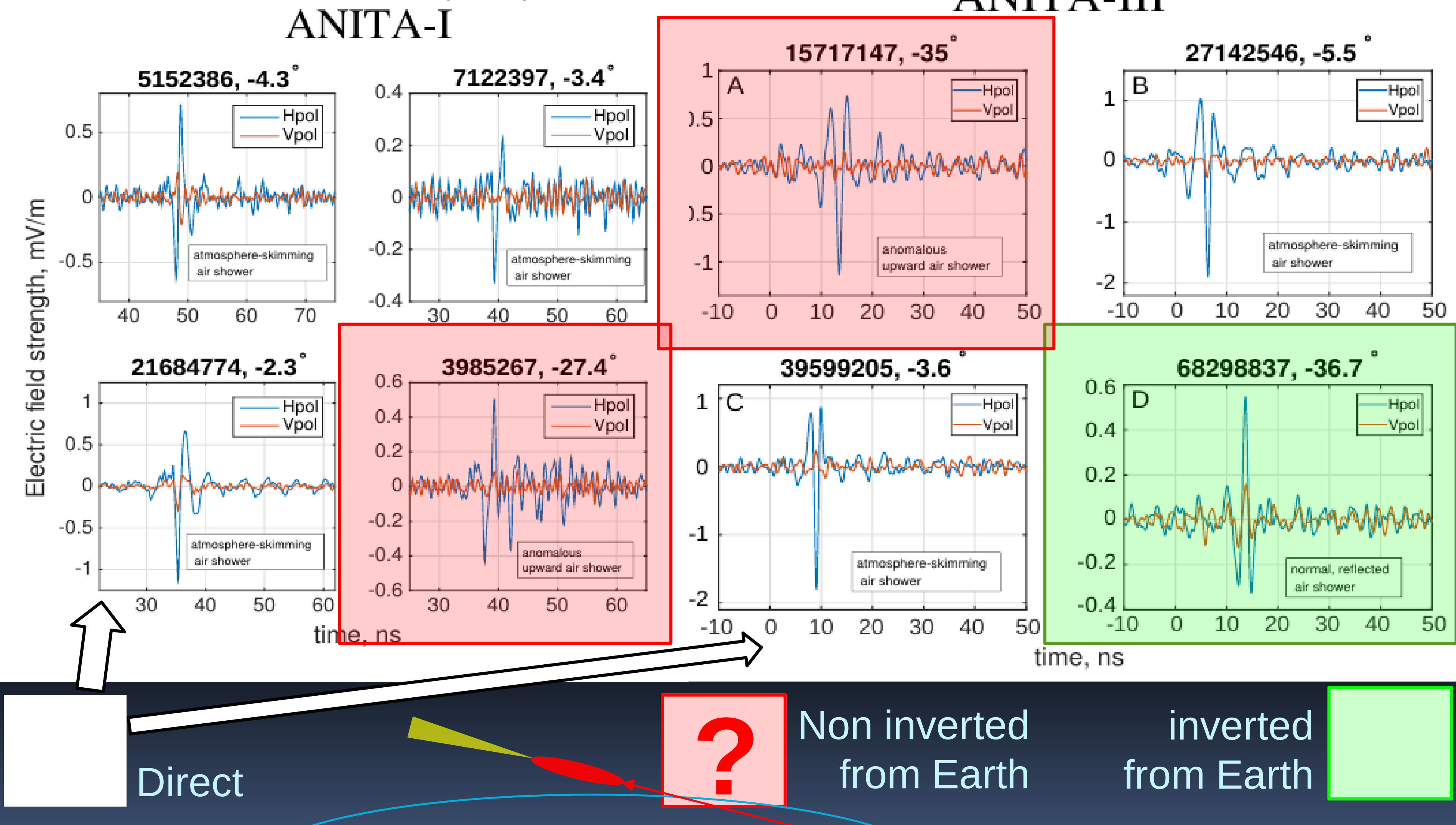




[S. Hoover et al., Phys.Rev.D 99 (2019) 12, 122001]

Intriguing events are horizontally polarized: Air showers

P.W. Gorham et al., PRL 117 (2016) 7, 071101

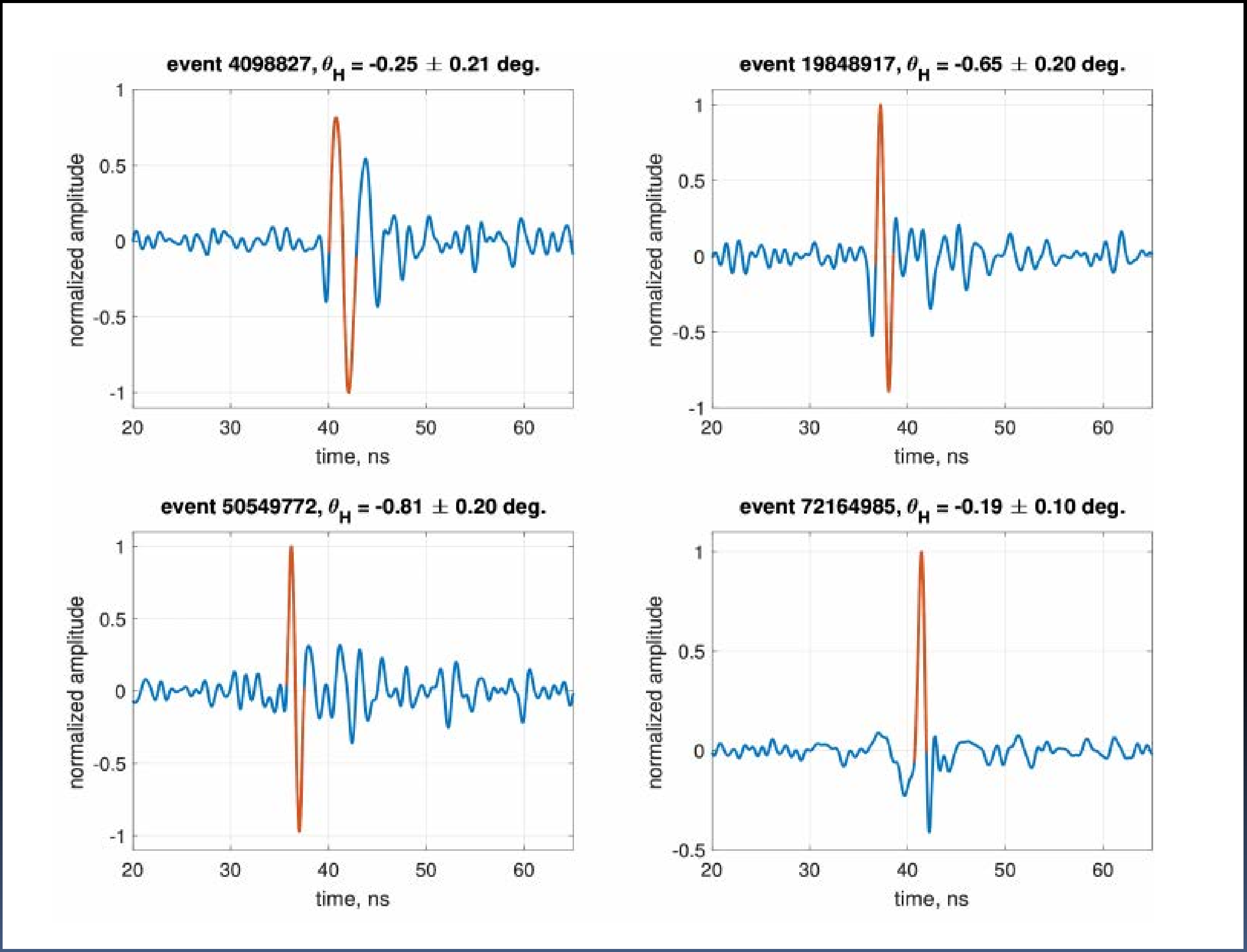


Inconsistent with SM because of absorption

[A. Romero-Wolf et al., PRD 99 (2019) 6, 063011]

ANITA IV has also non-inverted events from the Earth

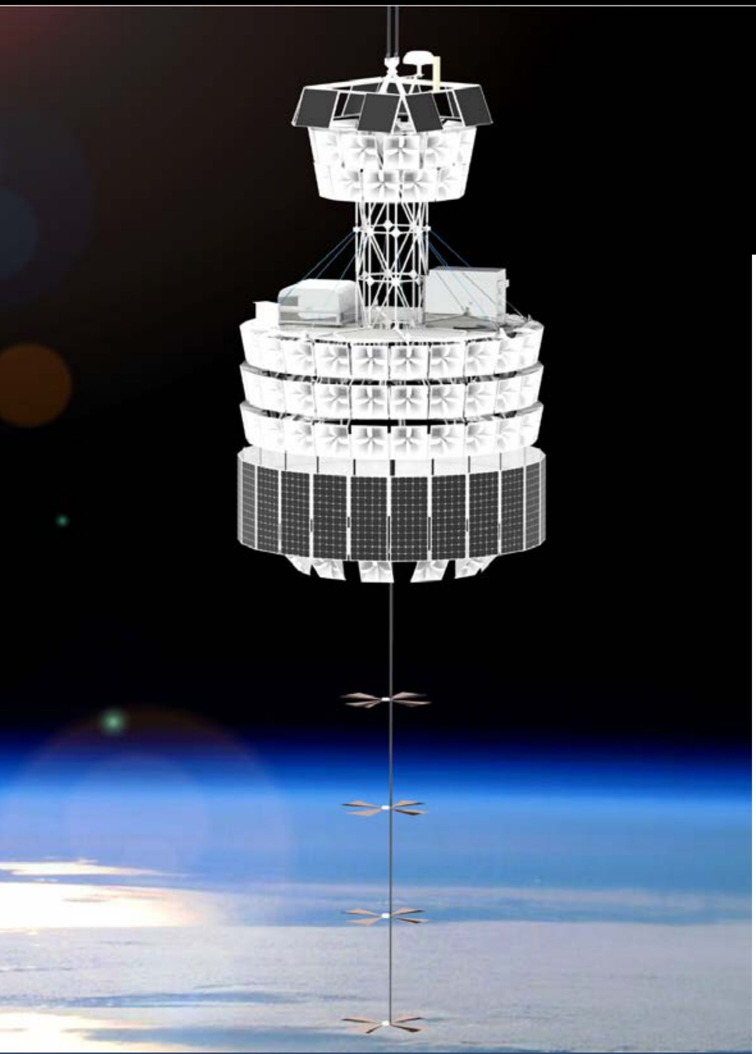
These are very close to the limb



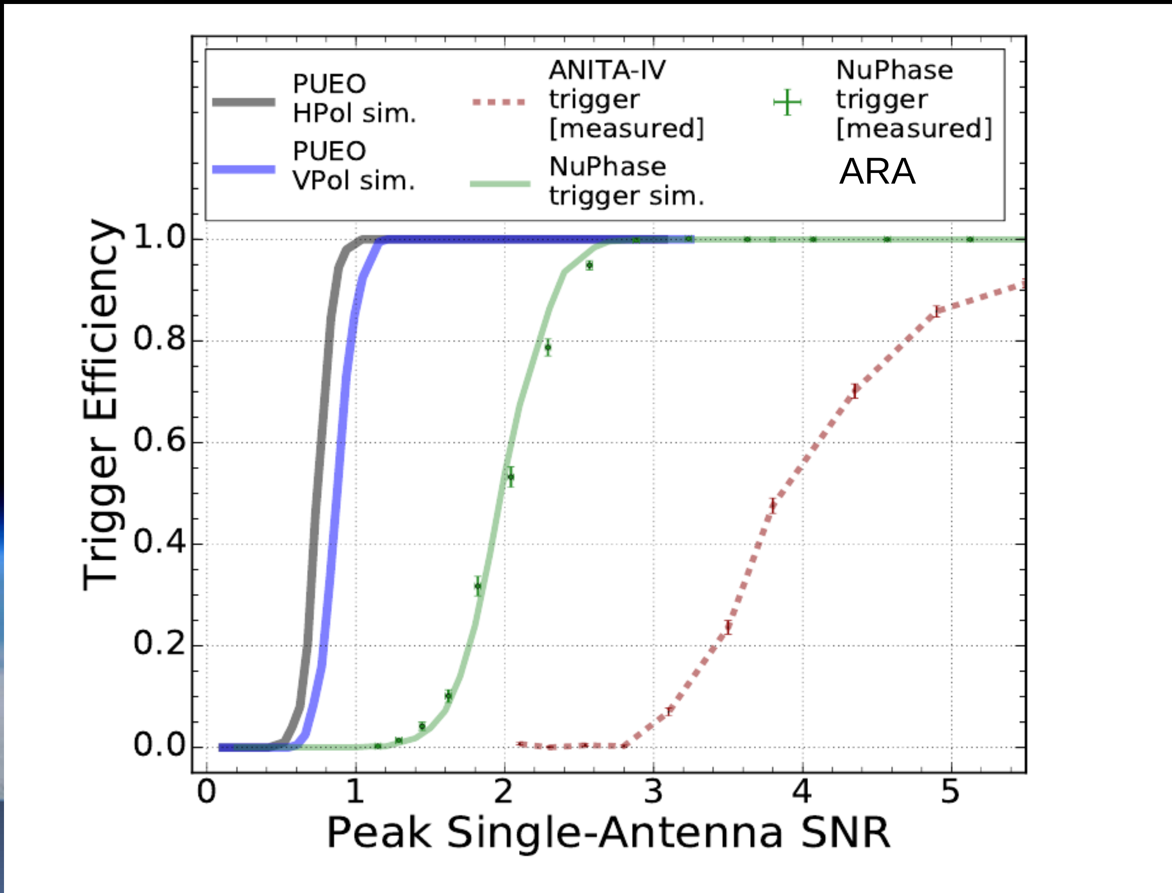
angles below horizon

P.W. Gorham et al., PRL 126 (2021) 7, 071103

Next instrument: PUEO



Phased trigger
Reduced horns more antenas
Huge trigger improvements: 10x sensitivity
NASA pioneers mission, 21

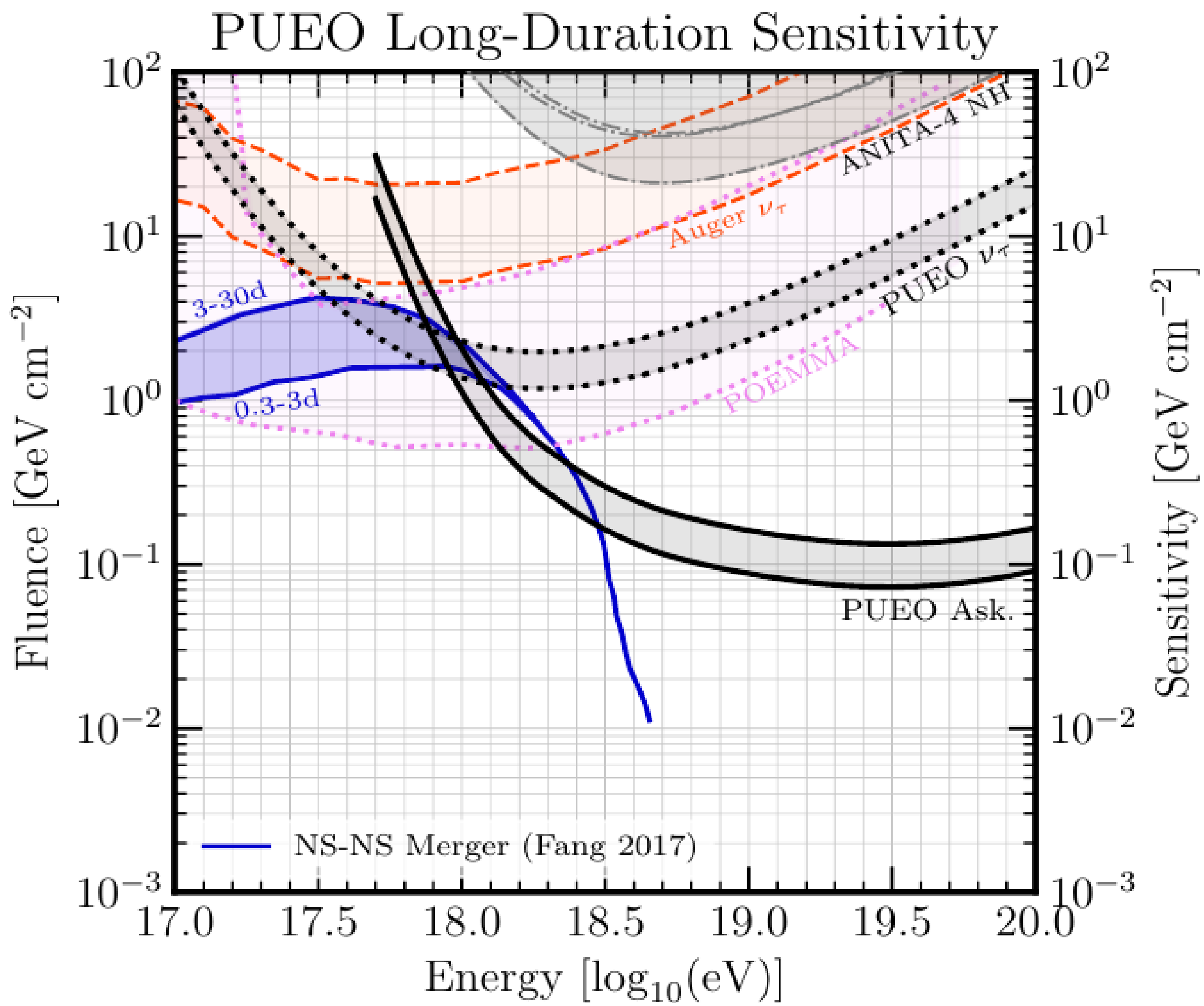


[Q. Abarr et al., JINST 16 (2021) 08, 08]

Exploiting the Earth Skimming channel

Enhanced Sensitivity in sub EeV band

point source

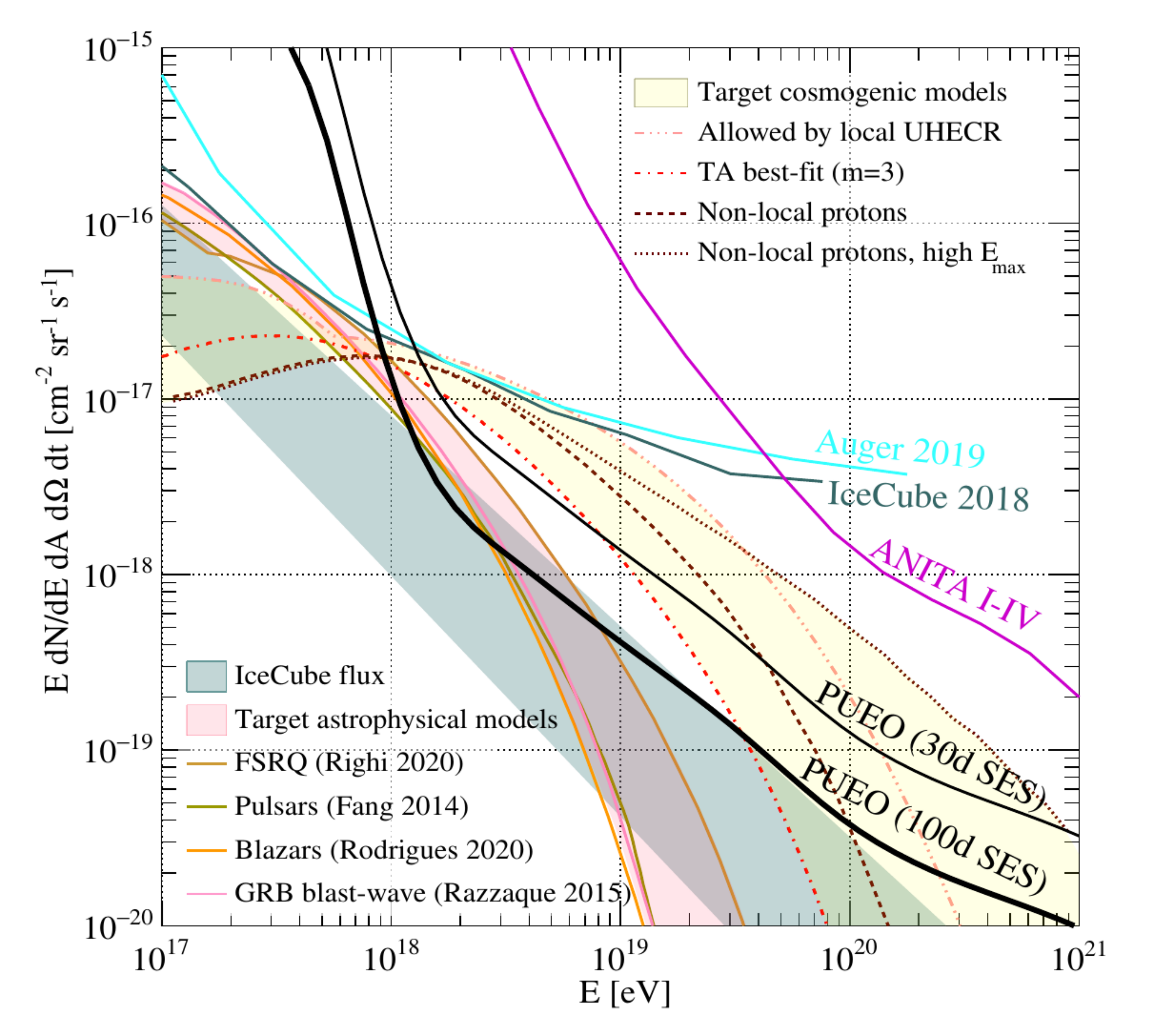


Diffuse sensitivity: PUEO

PUEO

↓

Extrapolation of IceCube data



Exploiting the Earth Skimming channel

Enhancement of existing projects viewing the atmosphere

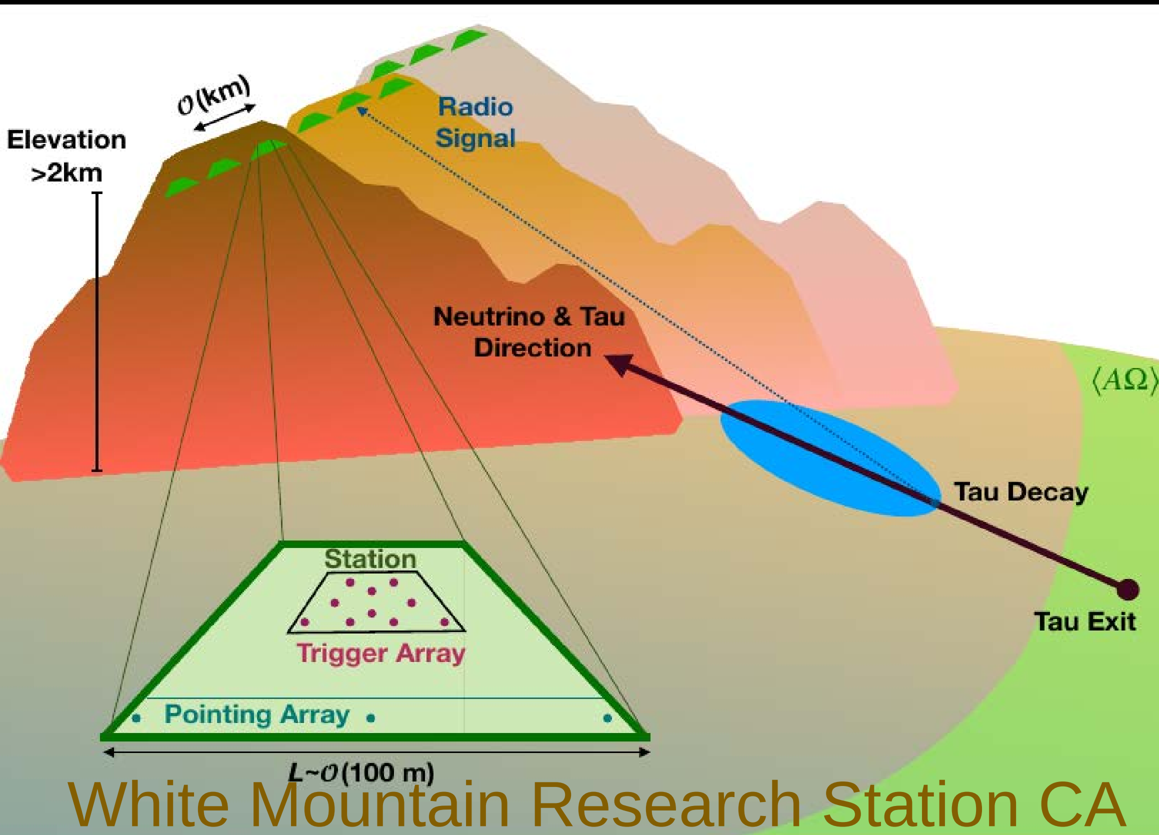
- Increased exposure
- Lower threshold
- Directionality
- Mostly tau sensitivity

Optical Poemma, EUSO-SPB
Radio ANITA
Particles Auger

New initiatives target the ES channel

Optical TRINITY
Radio GRAND, BEACON, PUEO
Particles TAMBO

Radio from a mountain: BEACON, TAROGE



White Mountain Research Station CA

BEACON prototype
(2018-2023)

- Simulation
- Site characterization
- Deploy and validate CR

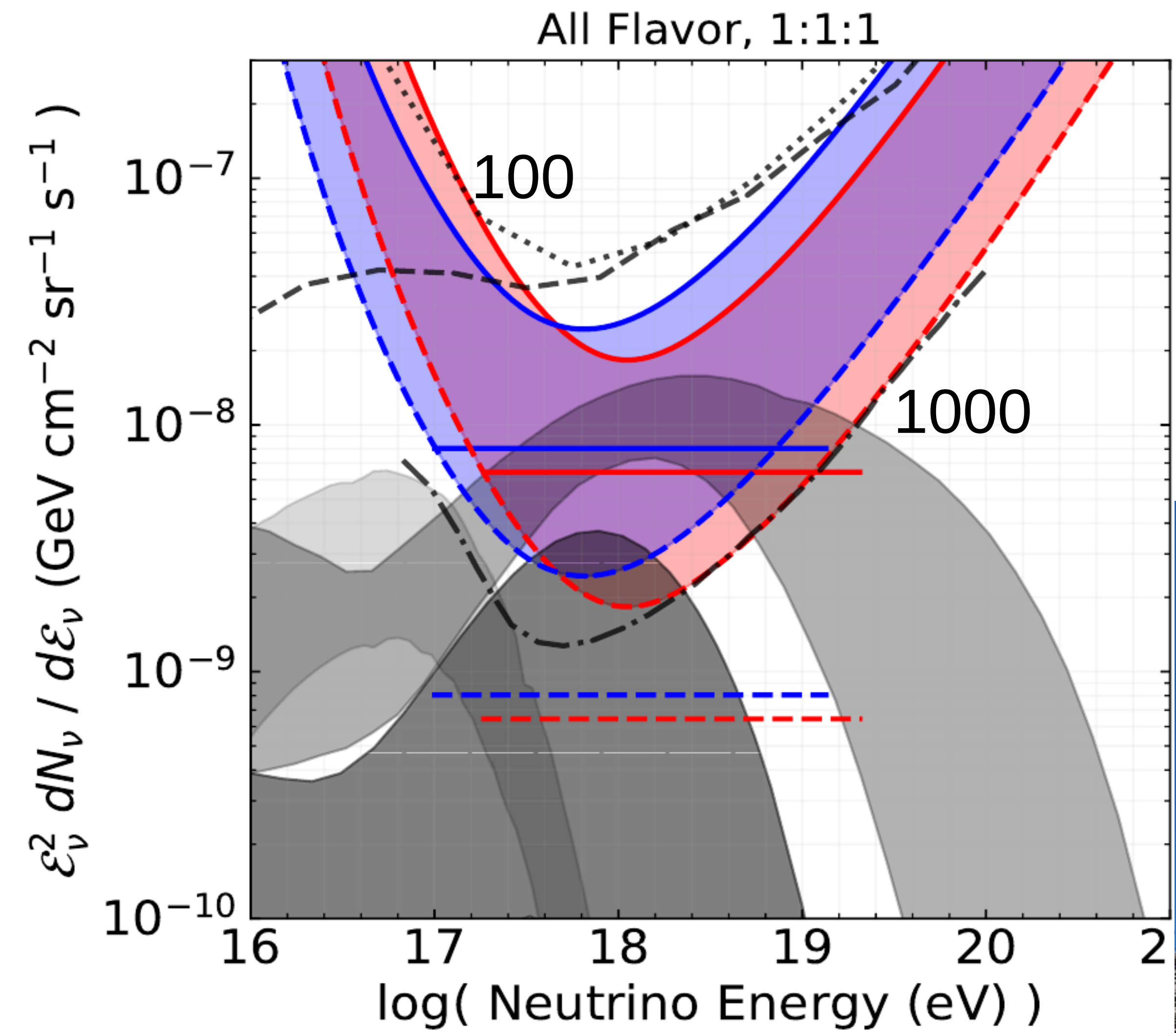
[S. Wissel et al., JCAP 11 (2020) 065]

Phased + pointing
100-1000 stations
Flexible concept

- Waveband
- Altitude > ~2 km
- N of antennas ~10
- Multiple locations

TAROGE-M station
top of Mt. Melbourne Antarctica

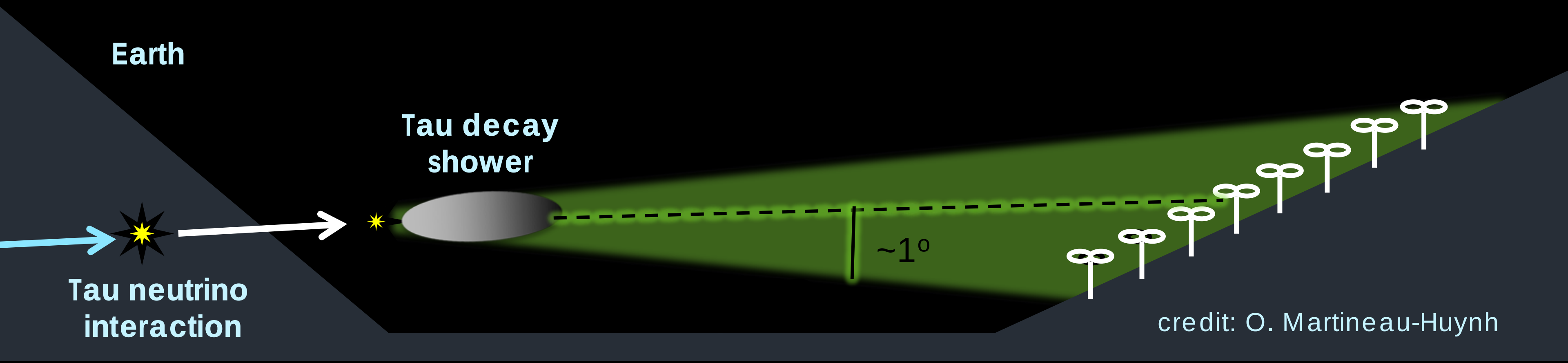
[J.W. Nam et al., int. J. Mod. Phys D25 (2016) 13, 1645013]

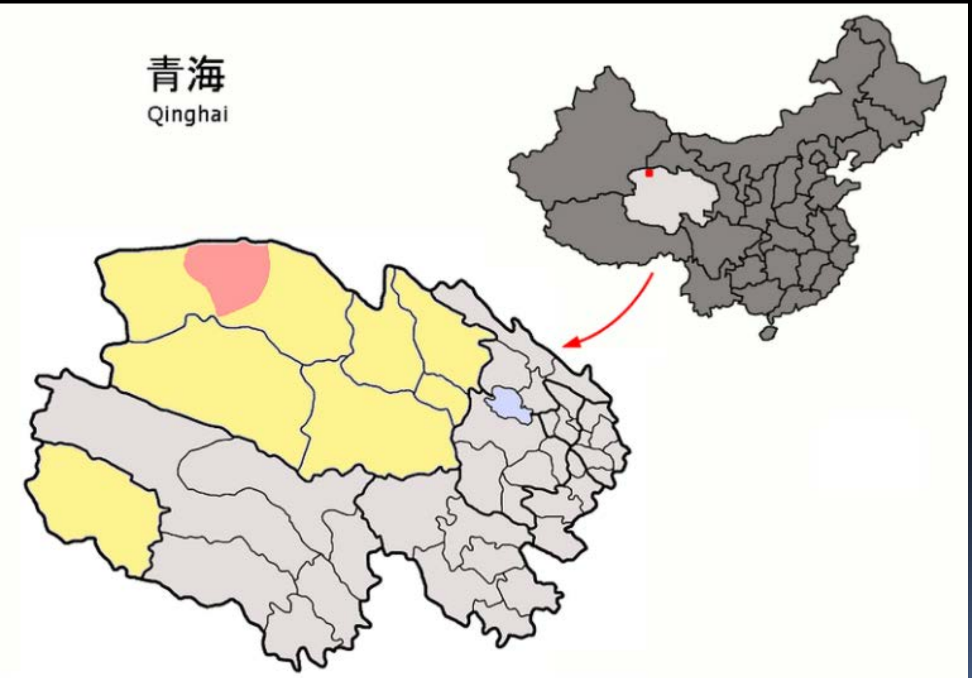


2 bandwidths + 2 sizes: 3 years

Diffuse sensitivity: BEACON

GRAND: Giant Radio Array for Neutrino Detection





~2015

~ 200,000 antennas self-triggering

200,000 km² 20 x 10,000 km² arrays

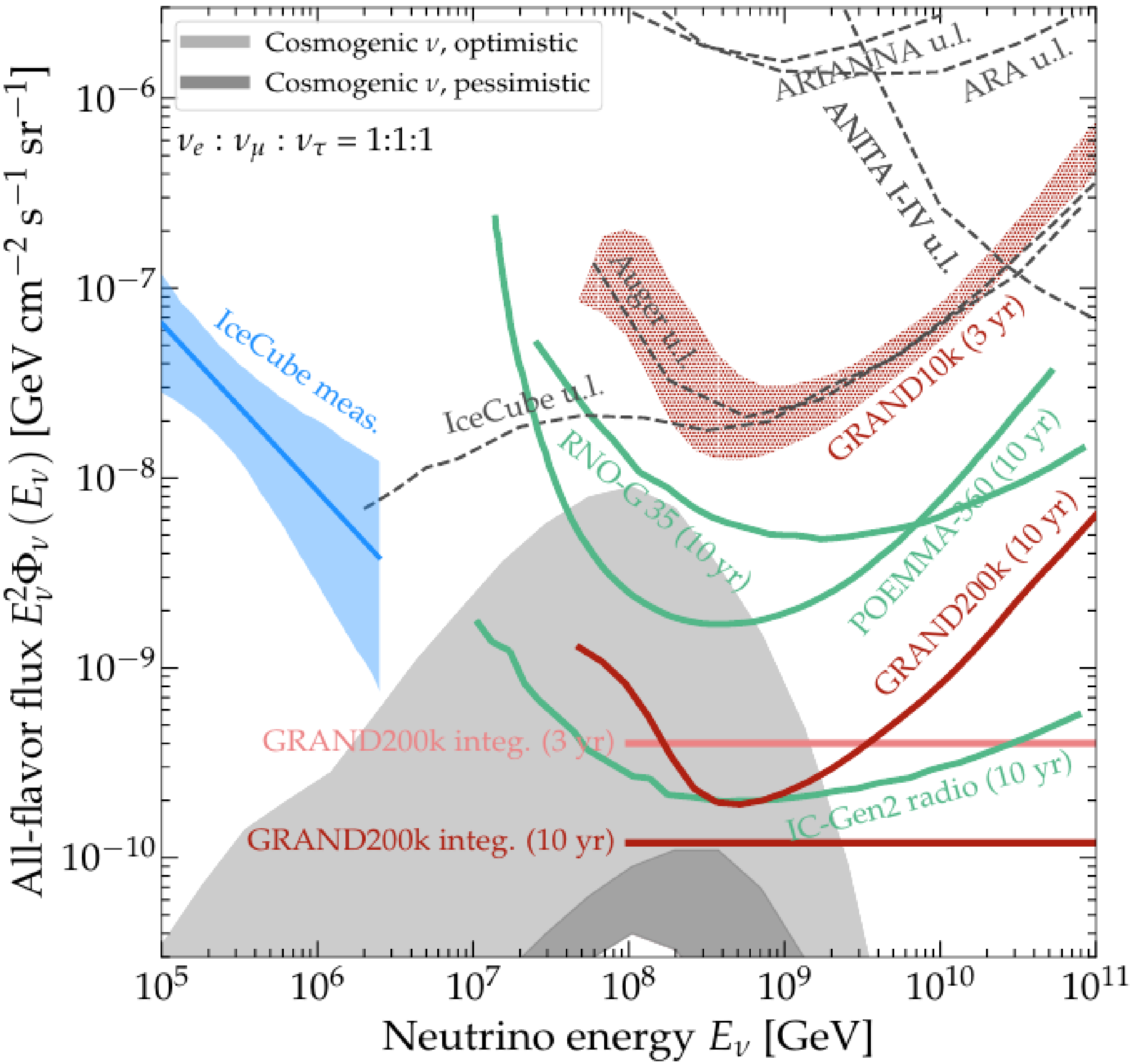
Valley in Mountaineous site

50-200 MHz

Targets CR too

- **GRANDproto35 (35 ant+24 scint)**
- **GRANDproto300 (starting ~2021)**
- **...**

[Q. Abarr et al., Sci China Phys.Mech.Astron. 63 (2020) 1, 219501]
[K. Kotera, PoS ICRC2021 (2021) 1181]



Cosmogenic ν, optimistic
Cosmogenic ν, pessimistic
$\nu_e : \nu_\mu : \nu_\tau$ = 1:1:1
IceCube meas.
IceCube u.l.
ARIANNA u.l.
ARA u.l.
ANITA I-IV u.l.
Auger u.l.
GRAND10k (3 yr)
RNO-G 35 (10 yr)
POEMMA-360 (10 yr)
GRAND200k (10 yr)
GRAND200k integ. (3 yr)
GRAND200k integ. (10 yr)
IC-Gen2 radio (10 yr)
All-flavor flux $E_\nu^2\Phi_\nu(E_\nu)$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]

The Earth skimming technique selects tau neutrinos

The radio technique has many advantages

Many competing experiments and projects

There are still chances of further exploiting the technique

Thank You