Radio detection of Ultrahigh-Energy Cosmic Rays and Neutrinos

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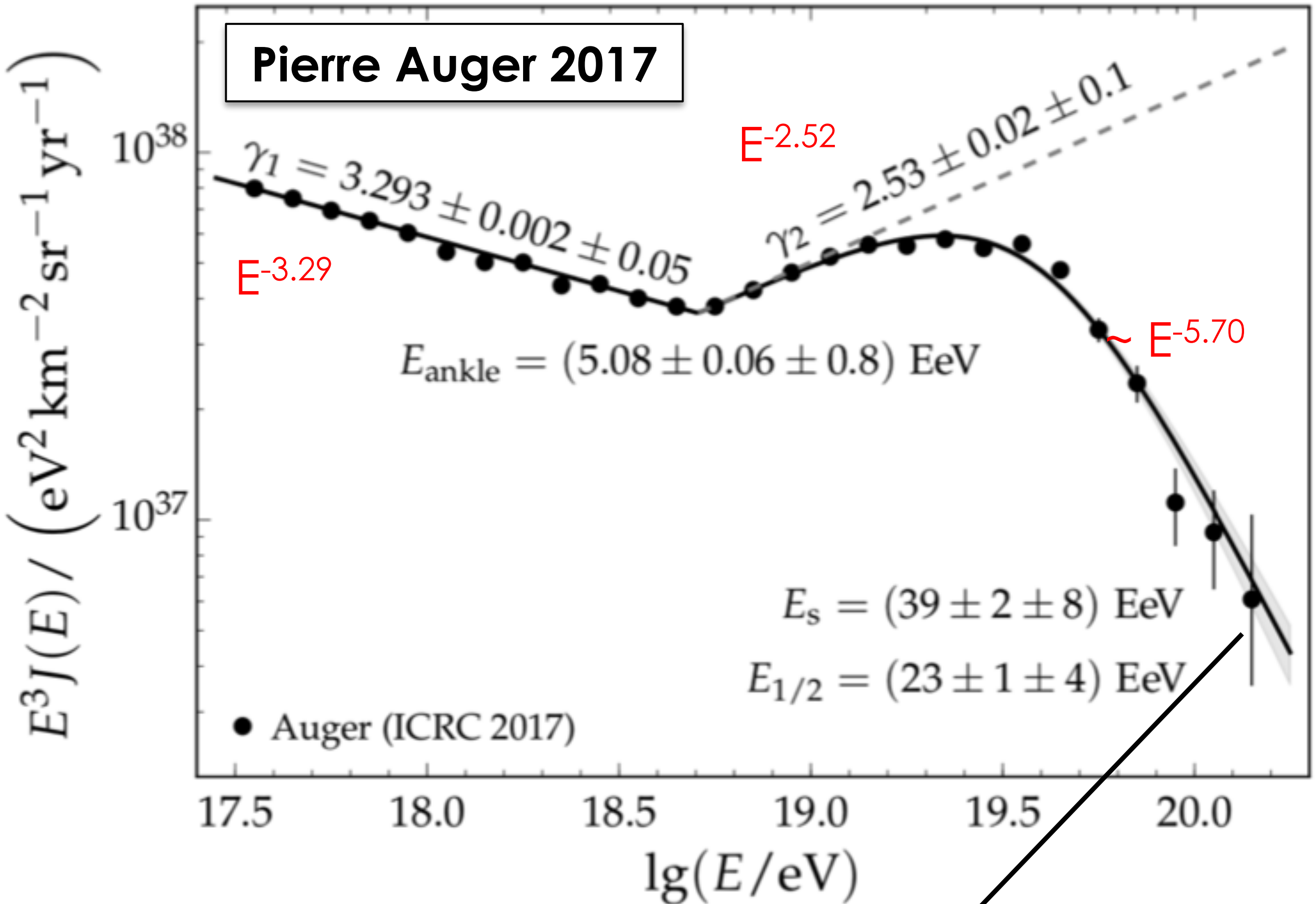
Ultrahigh-Energy Cosmic-Ray (UHECR) Flux



Cosmic-ray energies up to 10^{20} eV (~ 16 Joule) observed !! …but…

- Sources? Nature (protons, heavier nuclei,…)?
- What is causing flux suppression?,
  - Propagation in the CMB ($p\gamma \rightarrow p\ \pi^0$ or $n\ \pi+$ - the **GZK-effect**)
  - Sources run out of power ?

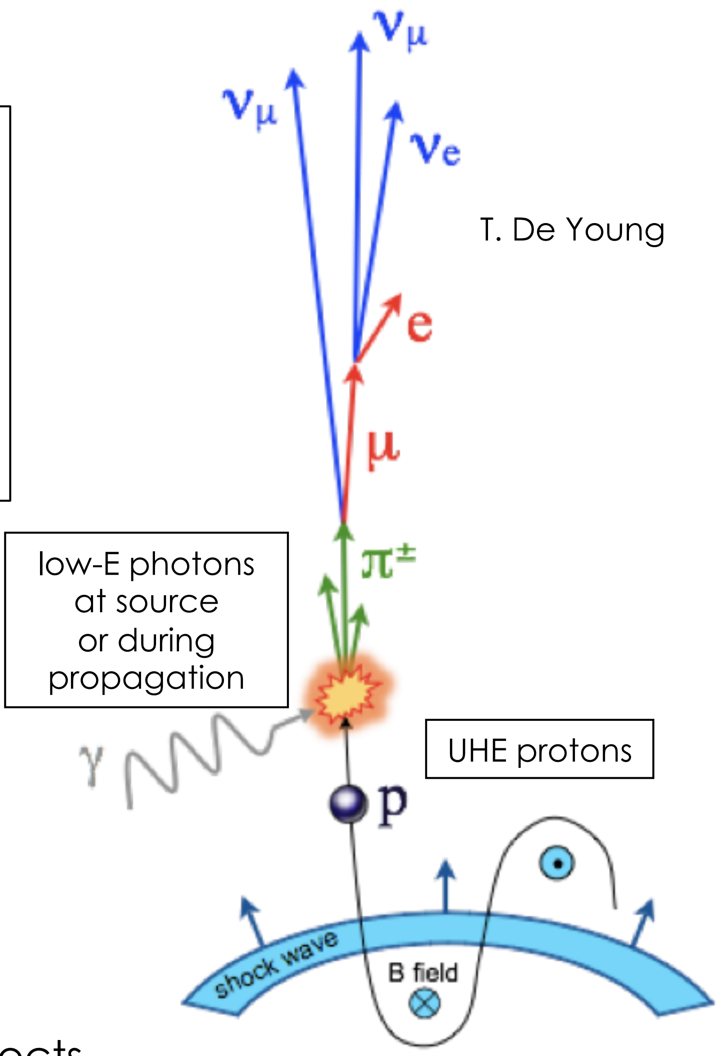
Cosmic neutrino beams

"Standard model" of neutrino production:

Cosmic Ray acceleration
+
UHECR interaction with matter
and/or radiation in/around source
and/or while propagating through Universe

Neutrinos are key messengers in the search for sources of UHECR

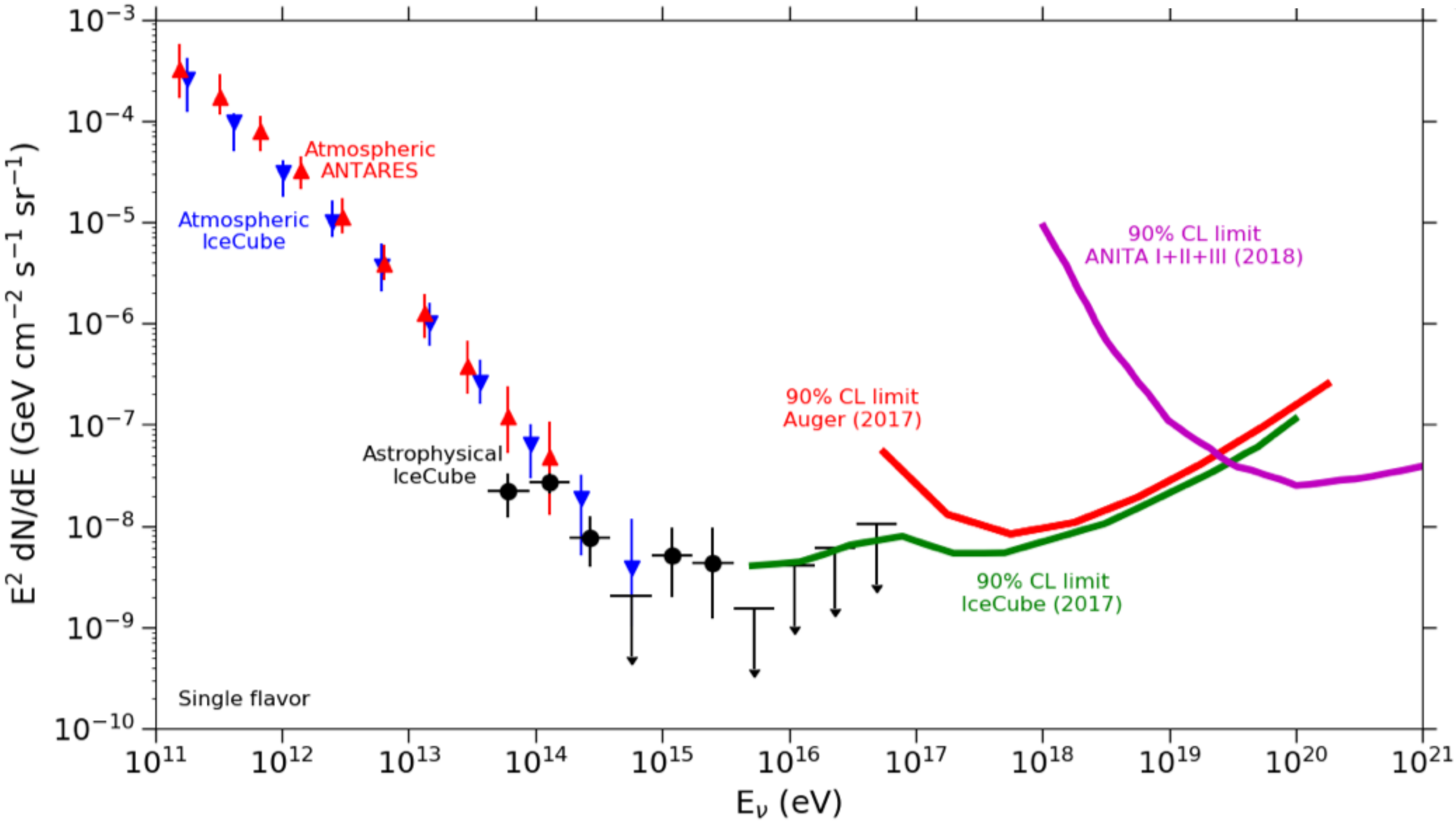
- ✓ **Not deflected** by Galactic/inter-gal. B-fields:
  - Point back to sources where they were produced
- ✓ **Travel unimpeded** along cosmological distances
  - Only messengers of high-redshifted Universe at UHE
- ✓ **Can escape** from dense cores of astrophysical objects
  - Probe the inner workings of sources
- ✓ **Reveal properties of sources of UHECR**
  - ✓ (z-evolution) not accessible through measurements of spectrum or composition



Pion photo-production

Neutrino fluxes: data & upper limits

J. A-M highlight talk ICRC 2017



The lack of neutrino observations above 10^{16} eV is driving an intense & exciting experimental activity

Radio detection technique

Idea:

measure radiation in **MHz – GHz** range emitted in **UHECR & ν-induced showers** in **atmosphere** or **dense dielectric media** (Antartctic ice,…)

Main advantages of radio technique

AIR:

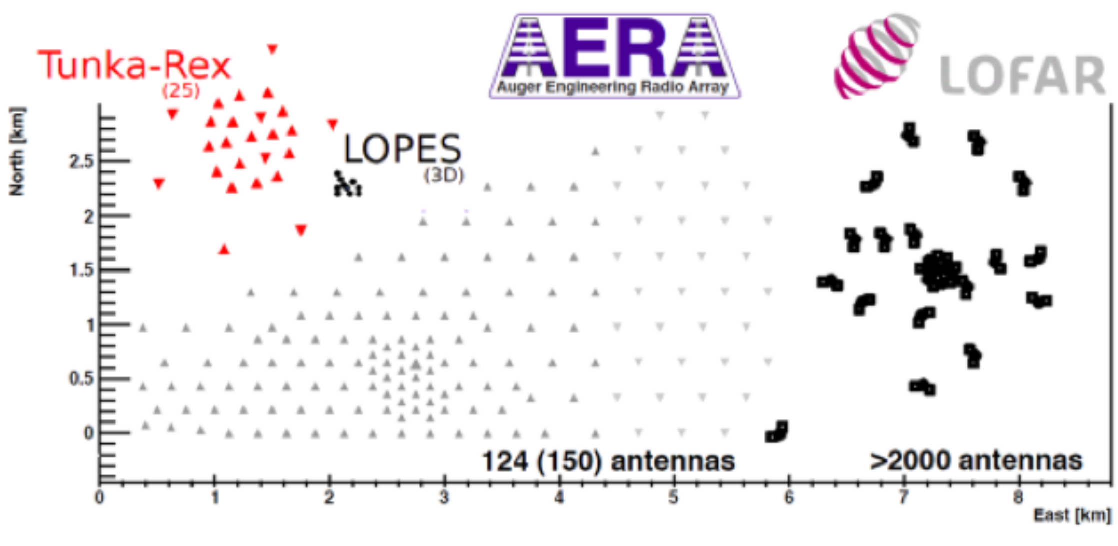
- ✓ Almost 100% duty cycle
- ✓ Calorimetric CR energy measurement
- ✓ Sensitivity to primary CR mass
- ✓ Relatively cheap & simple detectors: antennas
- ✓ Coherent emission i.e. Power ~ $(E_{CR})^2$ up to few 10's MHz

DENSE MEDIA: (density ~ 1 g/cm^3)

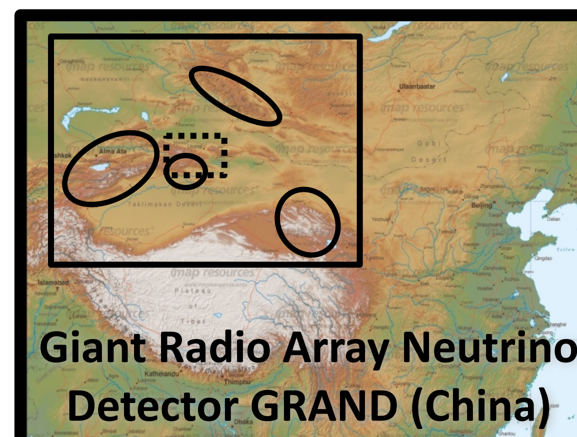
- ✓ ν interaction probability proportional to target density
- ✓ Large volumes of dielectric & transparent media in Earth (Antarctica)
- ✓ Cost-effective detectors: antennas
- ✓ Coherent emission up to few GHz

Experimental initiatives: air showers

Mainly ground arrays of antennas sensitive in the 10's MHz frequency range

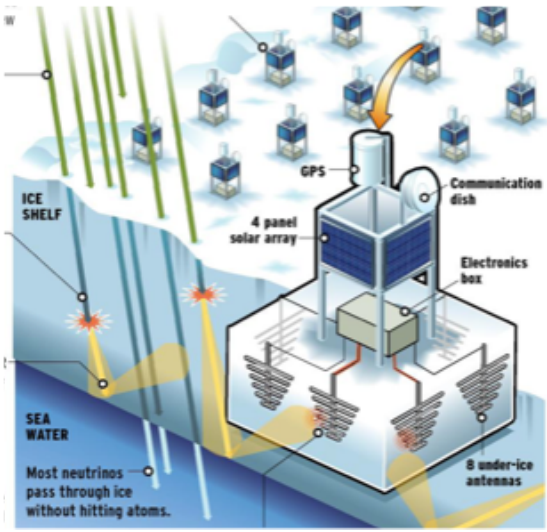


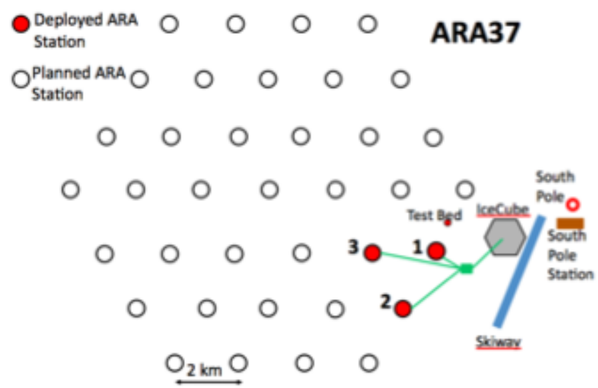
LOw-Frequency ARray (Netherlands)



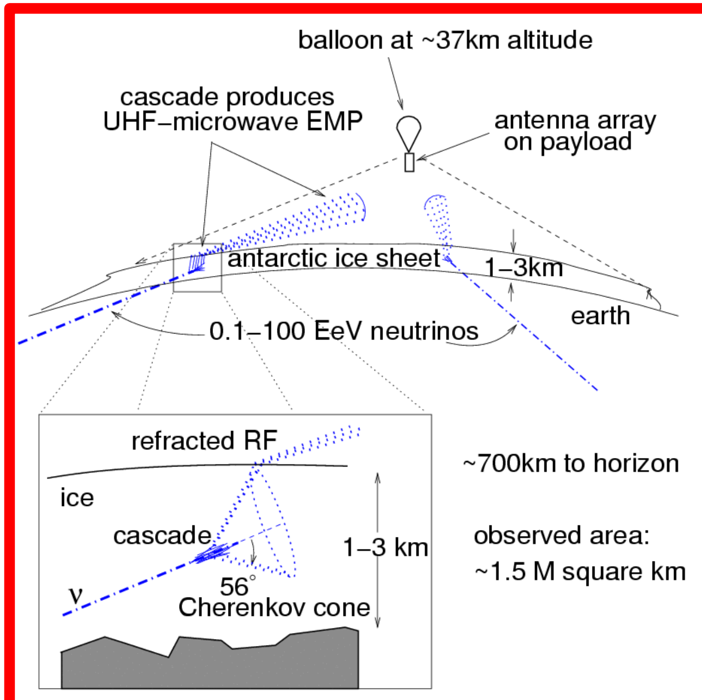
Experimental initiatives: dense media

Buried or balloon-borne arrays of antennas sensitive in the 100 MHz – GHz frequency range



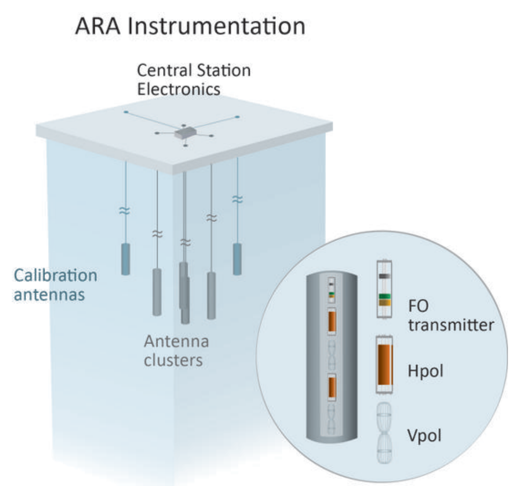


ARA



ANITA

ARIANNA



Radio-emission in showers:

- Moving charged particles radiate.

- In a shower most numerous charged particles are electrons & positrons:

  most radiation from electromagnetic component

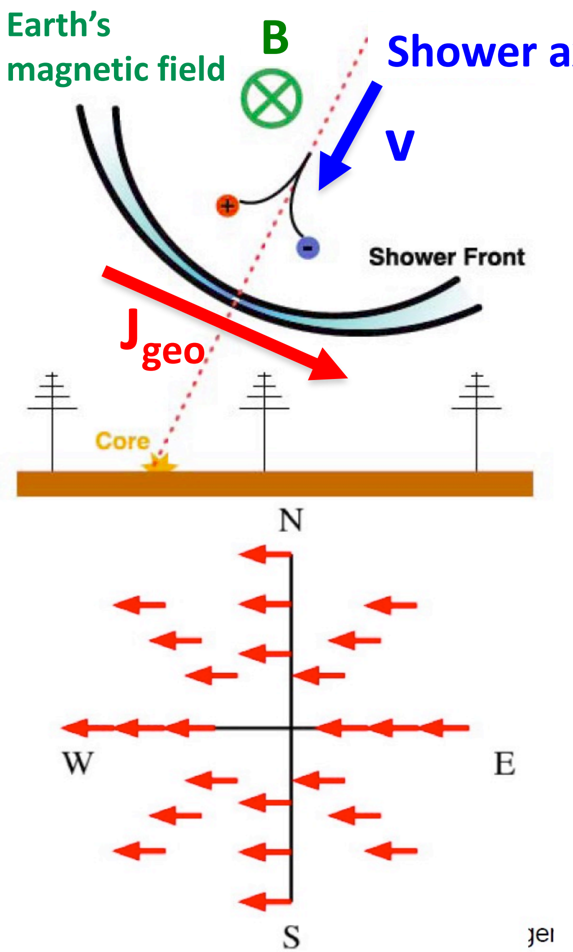
- …but… in a first approximation showers are neutral:

  e- & e+ are produced in equal numbers: $\pi^0 \longrightarrow \gamma\gamma \longrightarrow e^-e^+$

- …however, net charge (& hence radiation) is induced through 2 dominant mechanisms:

Geomagnetic mechanism

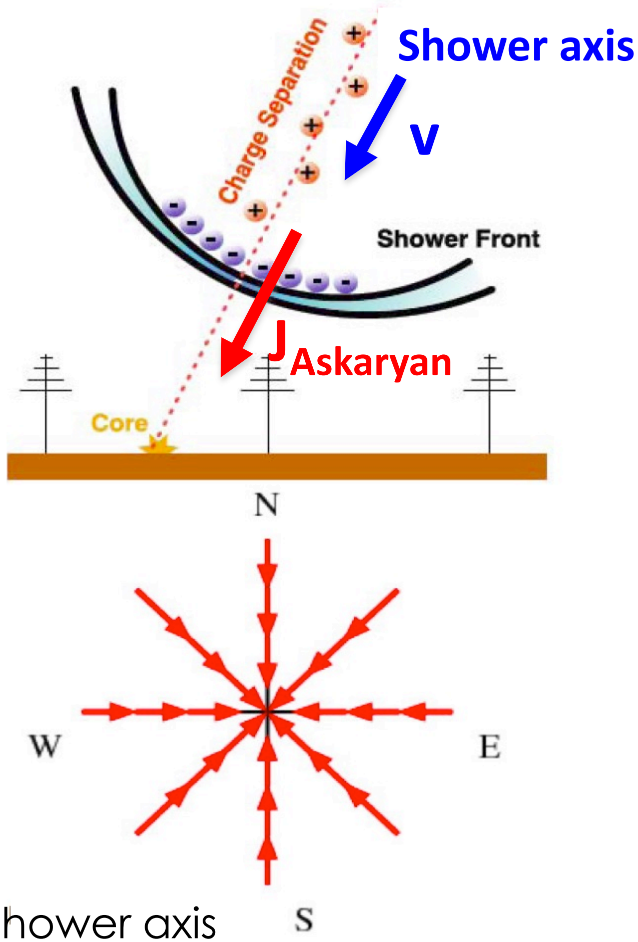
Separation of e- & e+ in the magnetic field (**B**) of the Earth induces **electric current** (J_{geo}) parallel to (**v x B**). **Electric field:** ~ B sinα (α = angle between **B** and **v**).



Charge-excess (Askaryan) mechanism

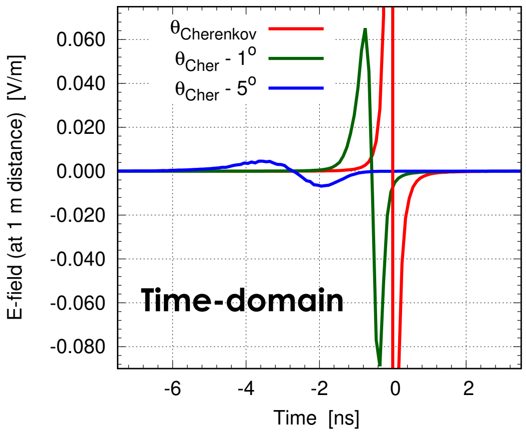
~ 20% **excess e- over e+** because shower drags atomic e- of atmosphere into shower flow, mainly due to Compton:

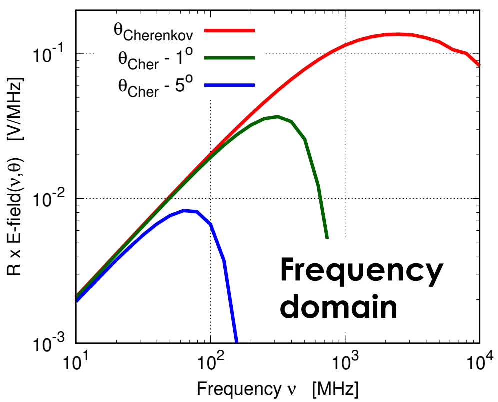
γ **e-(medium)** ⟶ γ **e-(shower)**

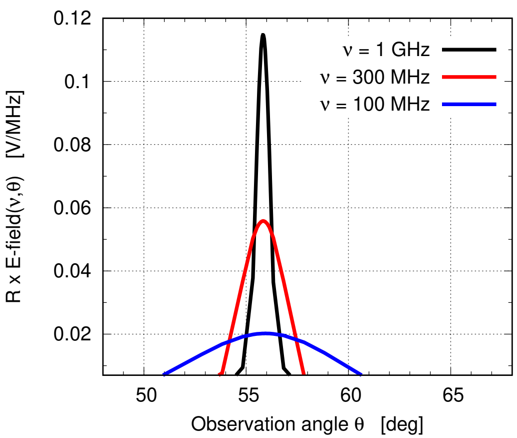


Approx. polarization pattern on shower plane around shower axis

Electric field: Monte Carlo simulations at IGFAE



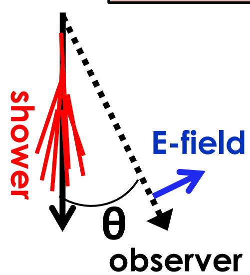


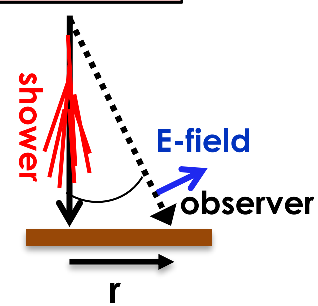


Ice (ZHS code)

Air (ZHAireS code)

Bipolar nano-second pulses



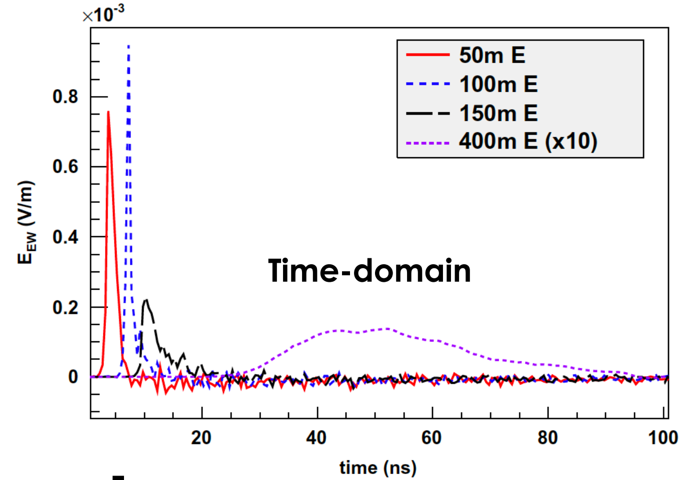


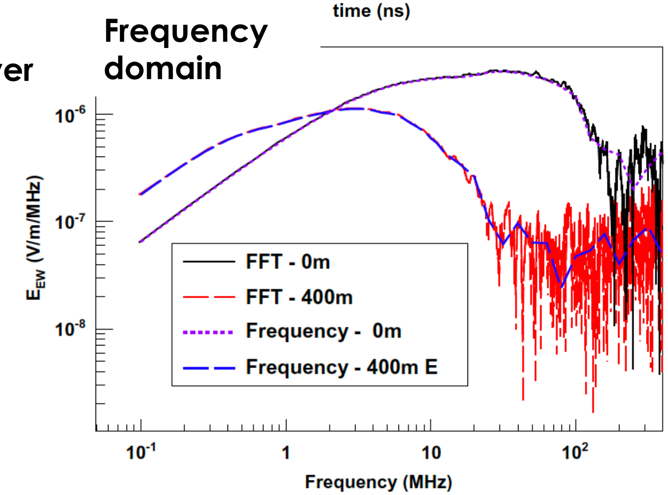
Broad-band frequency spectrum

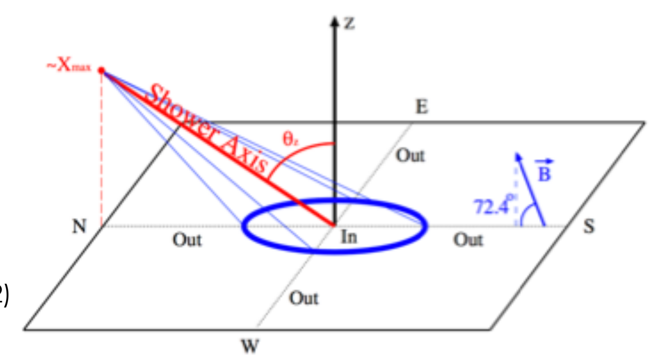
Radiation beamed at Cherenkov angle
~ 56° in ice
~ 1° in air

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

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





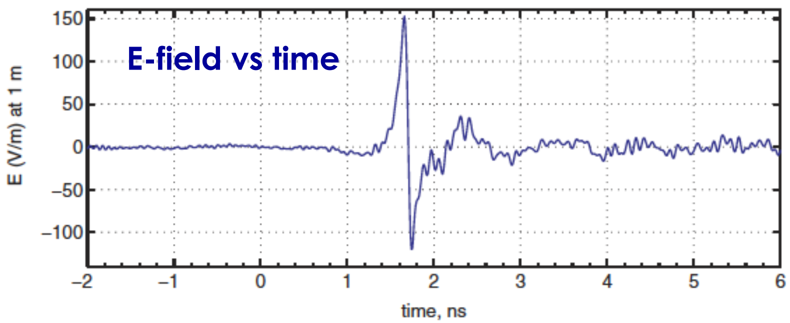


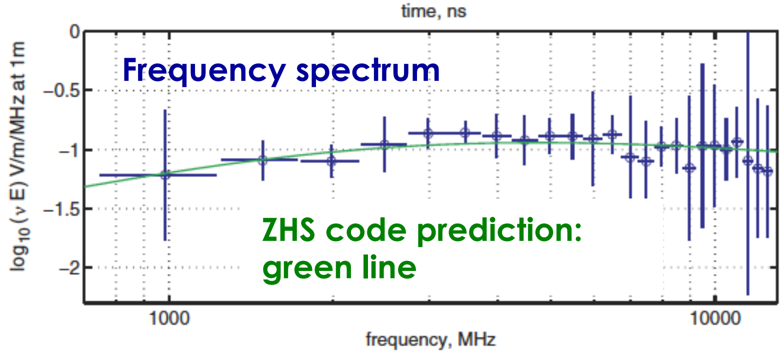
Data vs MC modeling

Salt

Test Beam at SLAC

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



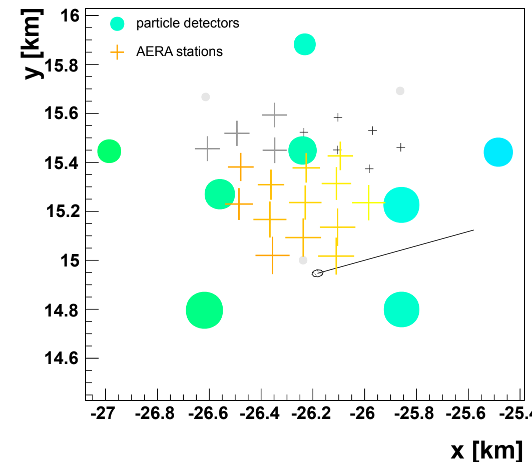


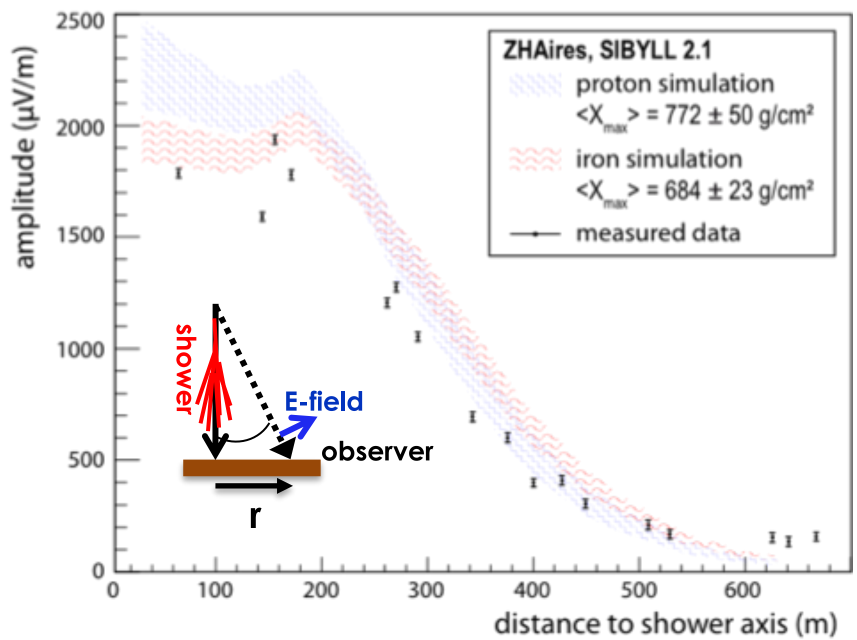
- **Askaryan effect observed**
- Power in radio waves increases as E_0^2
- **Bipolar nano-second pulses**
- Agreement with theoretical expectations

E. Zas, F. Halzen, T. Stanev, PRD **45**, 162 (1992);
J. A-M, A. Romero-Wolf, E. Zas, PRD **81**, 123009 (2010)
P.Miocinovic et al. PRD **74**, 043002 (2006);
P. Gorham et al. PRL **99**, 171101 (2007);...

Air

UHECR event detected with **AERA radio array** at Auger

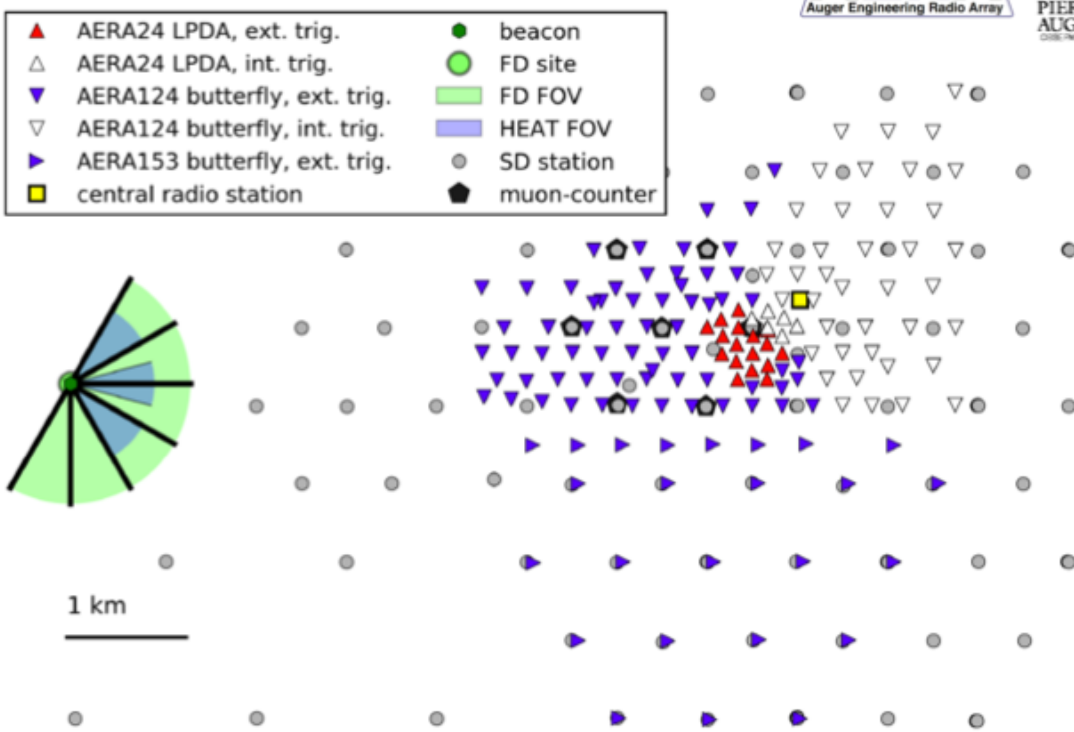




J.A-M, W.R. Carvalho, E.Zas, Astropart. Phys. **35**, 325 (2012)
H. Schoorlemmer, J.A-M.,…

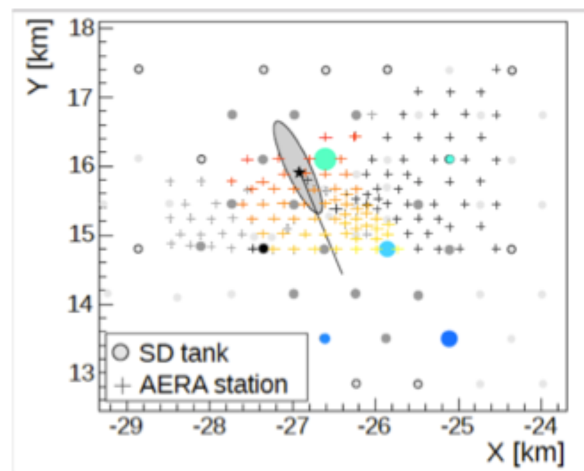
AERA:
Auger Engineering Radio Array

- Radio extension of the Pierre Auger Observatory
- Array of 153 antennas covering 17 km^2
- Events measured simultaneously with antennas and water Cherenkov stations



“Butterfly” antenna
30 – 80 MHz.
NS & EW polarizations

Radio & SD event



Cosmic-Ray energy determination in AERA

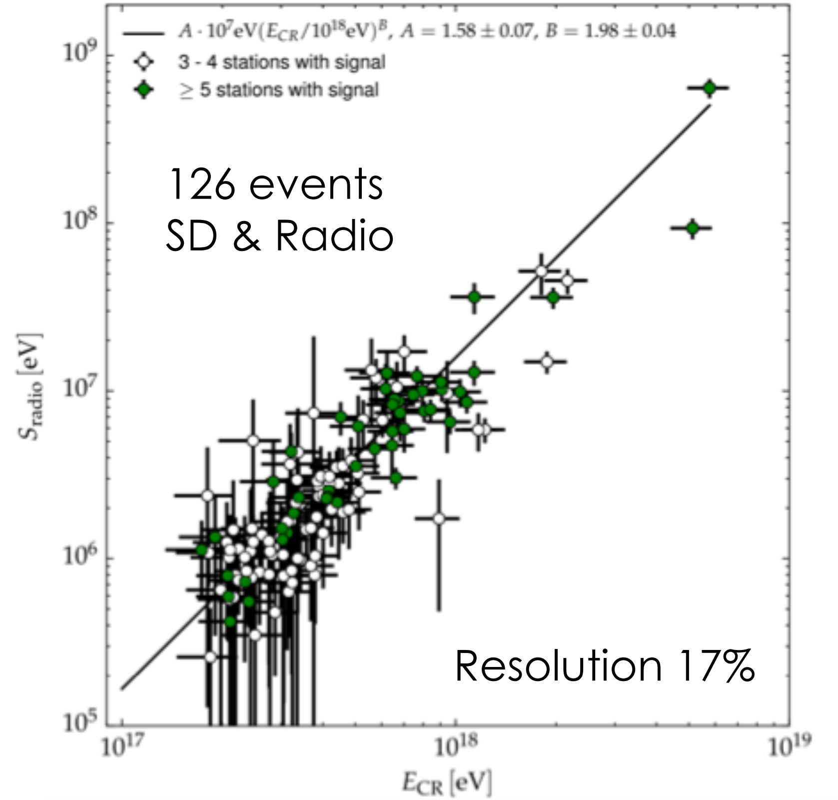
Energy emitted in radio in an event:

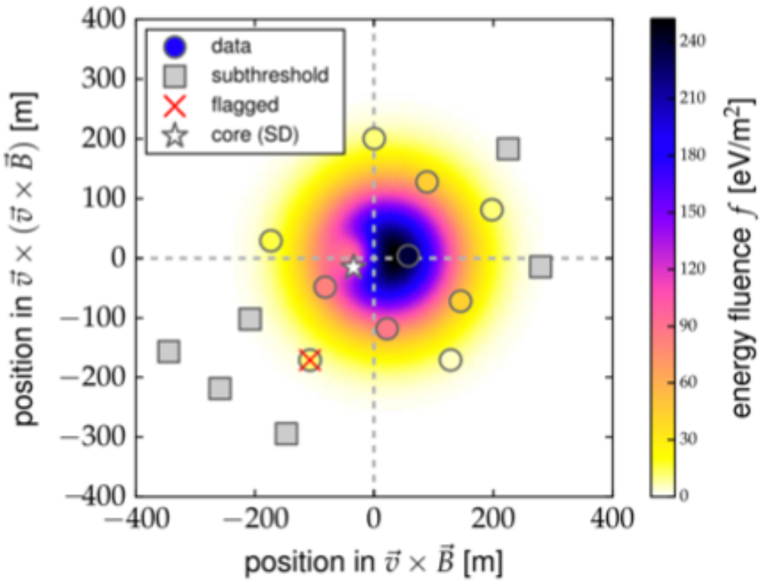
Single station data: obtain energy fluence eV/m^2

Fit to a 2D Lateral Distribution Function.

Integrate LDF in (x,y), obtain total energy emitted in radio (S_{radio}) for each event.

Cross-calibrate S_{radio} with E_{CR} using events detected simultaneously with Auger SD & AERA





Data: E_{radio} = 15.8 +/- 6.7 (sys) for $E_{CR} = 10^{18}$ eV

ZHAireS simulations: E_{radio} = 11.3 MeV for $E_{CR}=10^{18}$ eV

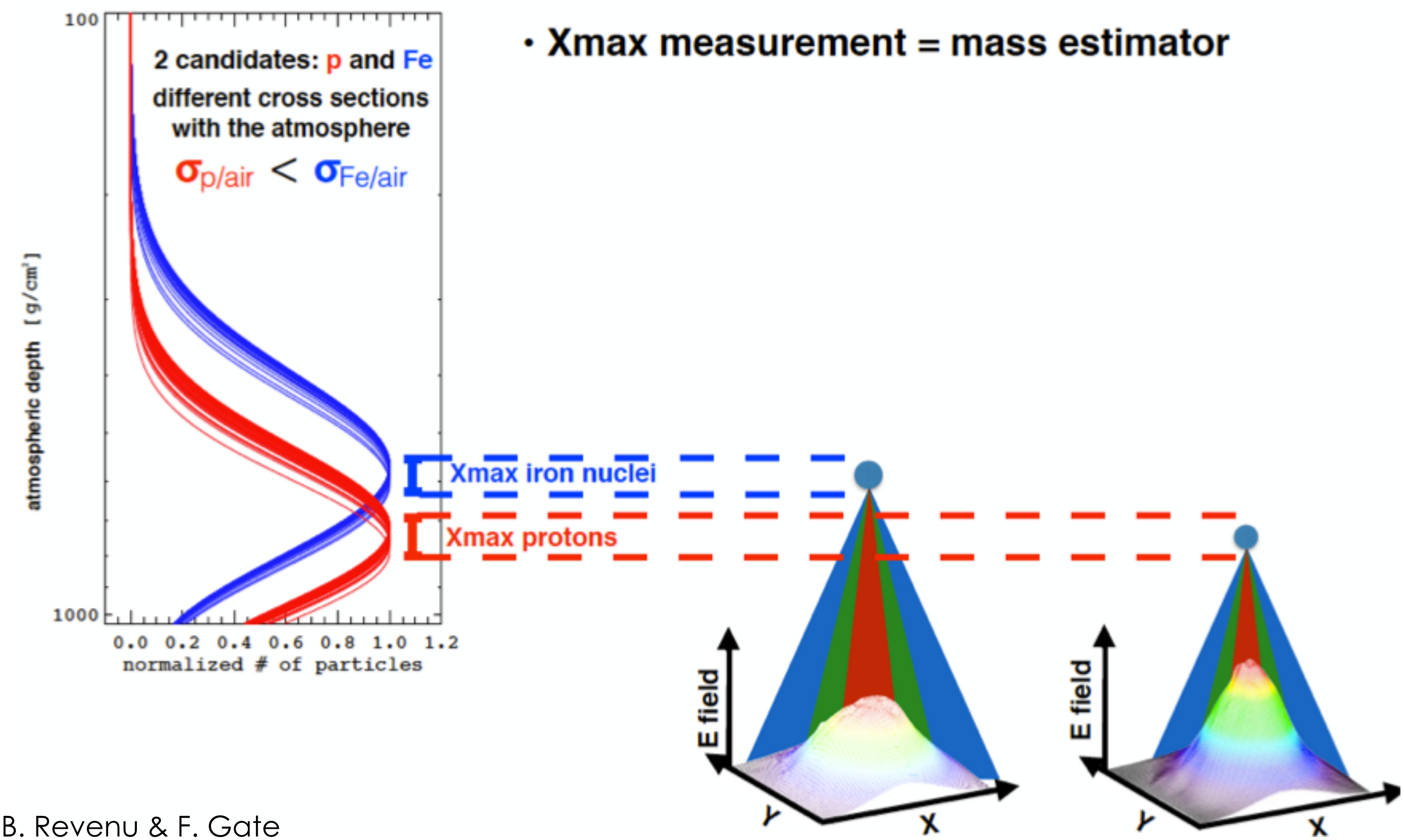
Radiation energy can be used for calibration of CR energy across different experiments !

Pierre Auger Collab., Phys. Rev. Lett. **116**, 241101 (2016), Pierre Auger Collab., Phys. Rev. D **93**, 122005 (2016)

Primary Cosmic-Ray mass composition with AERA

The **shape of the 2-dimensional distribution of the electric field amplitude** at ground depends on the mass of the primary:

- ✓ correlation of shape of radio footprint and depth of shower maximum X_{max}
- ✓ narrower 2D distribution for light nuclei compared to heavier nuclei



Credit B. Revenu & F. Gate

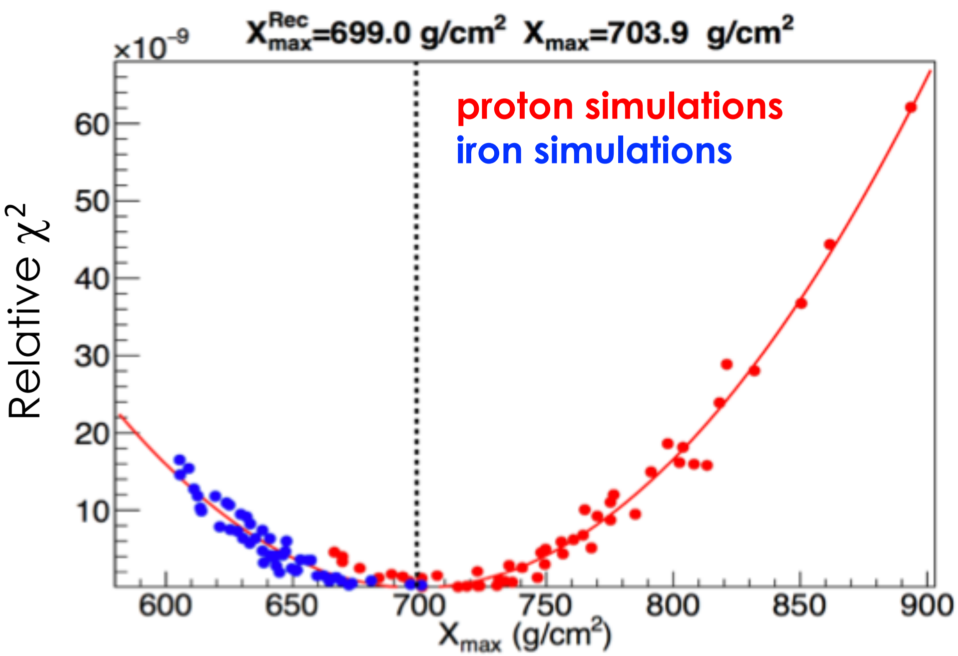
Primary Cosmic-Ray mass composition with AERA

Simple "brute-force" procedure to obtain X_{max} : For each detected event:

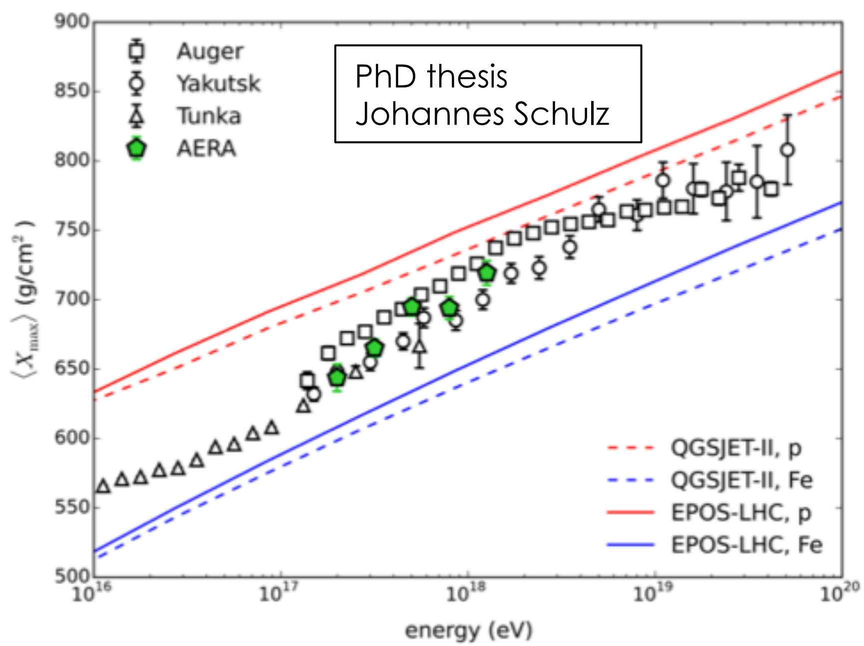
1. perform MC simulations of radio emission in showers with:
   - fixed energy & arrival direction (derived from data)
   - variable composition & X_{max}
2. Find the simulation that best fits data (minimum χ^2) => X_{max} value

Several analysis carried out at AERA. X_{max} resolution ~ 30 – 40 g/cm^2

Example of X_{max} reconstruction with radio

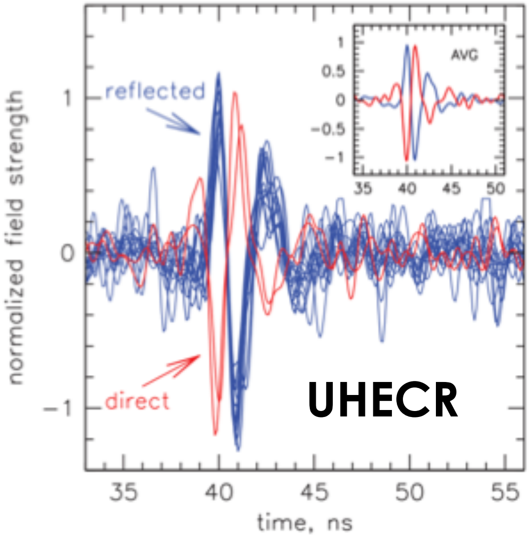


X_{max} vs energy using AERA data



Alternative method to determine primary CR mass by-passing the reconstruction of Xmax in J.A-M & W.R. Carvalho Jr. arXiv:1712.03544

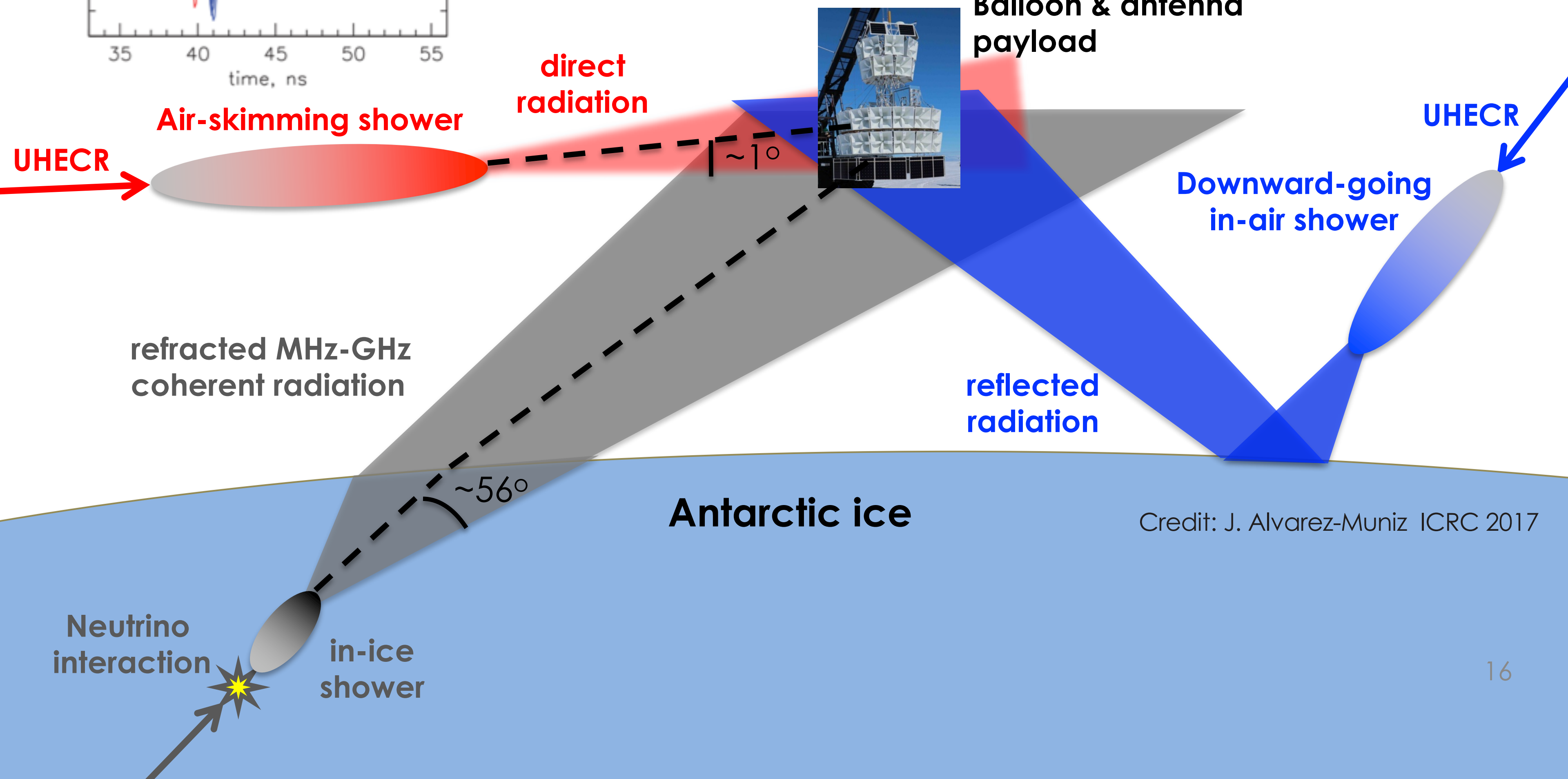
S. Hoover et al. ANITA Collab. Phys. Rev. Lett. **105**, 151101 (2010)



ANITA: ANtarctic Impulsive Transient Antenna

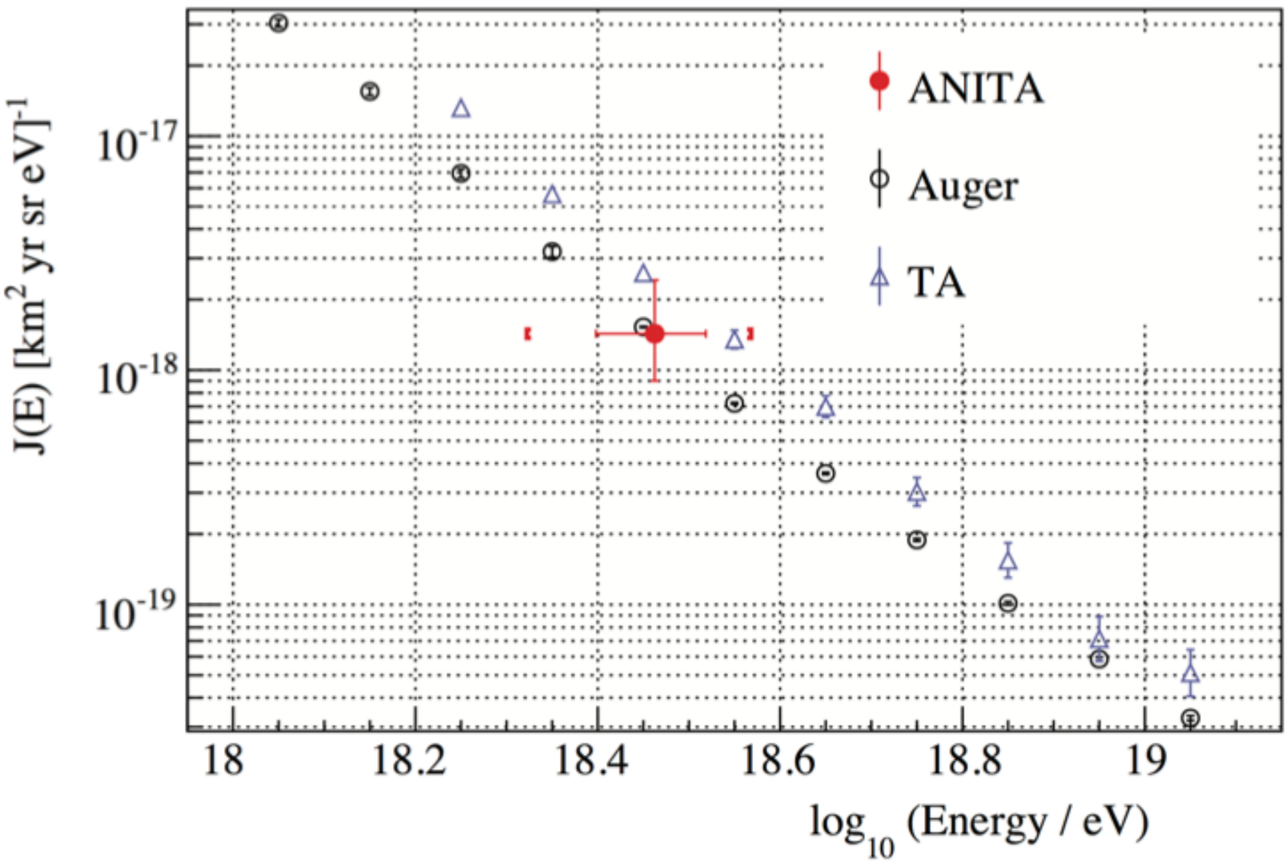
Balloon carrying antennas & flying for ~ 1 month around South Pole monitoring Antarctic ice

ANITA can detect both UHECR & UHE neutrinos



Credit: J. Alvarez-Muniz ICRC 2017

UHECR spectrum measured with ANITA



First UHECR flux derived only with radio

Obtained from 14 reflected events
(17 more seen in a later flight)

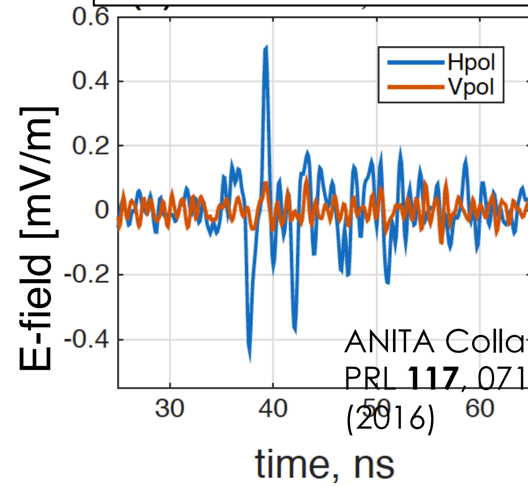
Energy reconstruction of events based on ZHAireS simulations at IGFAE

J. A-M, W.R. Carvalho Jr., D. García-Fernández, H. Schoorlemmer, E. Zas, Astropart. Phys. 66, **31** (2015).
H. Schoorlemmer,…, J.A-M, W.R. Carvalho, E. Zas & ANITA Collab., Astropart. Phys. **77**, 32 (2016).

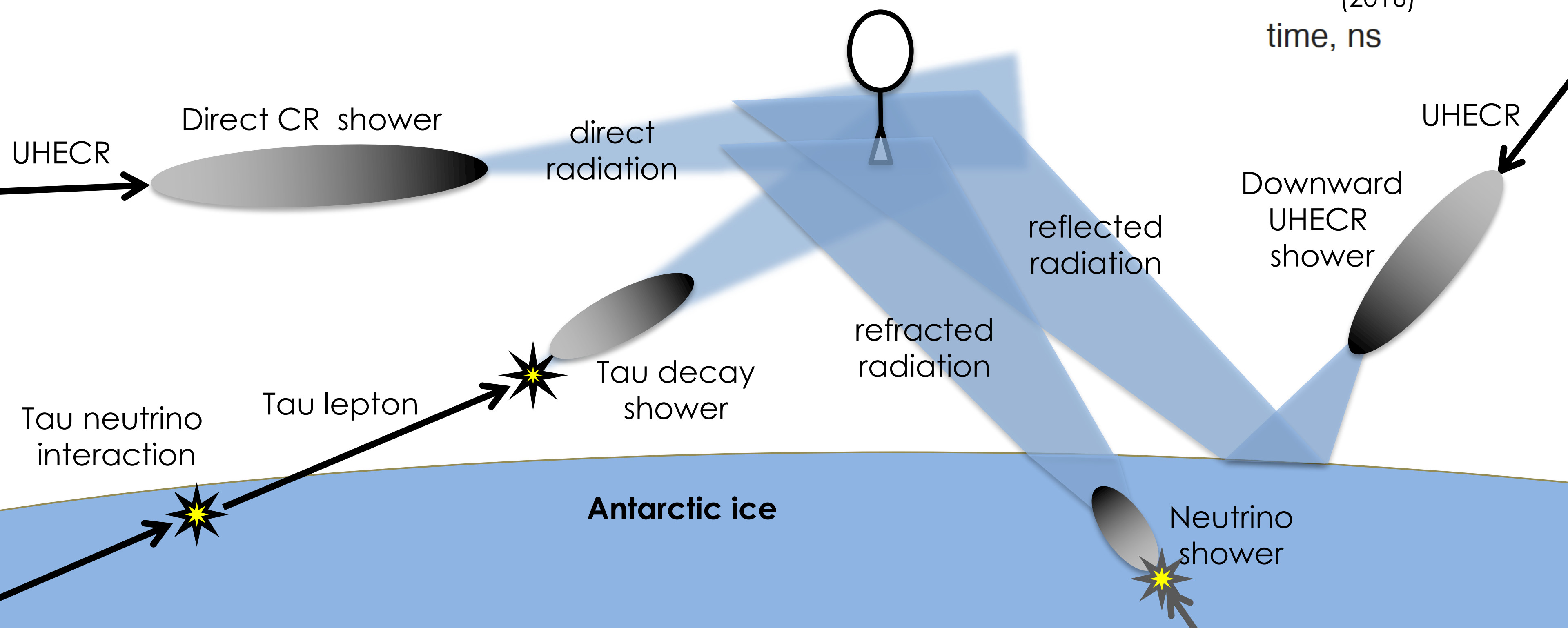
ANITA two upcoming events: are these tau neutrinos ??

- Arrived at payload **~27.4° & -35.0° below horizontal**

E ~ 0.6 +/- 0.4 EeV
-27.4 deg.



ANITA Collab.
PRL **117**, 071101 (2016)



ANITA two upcoming events: are these tau neutrinos ??

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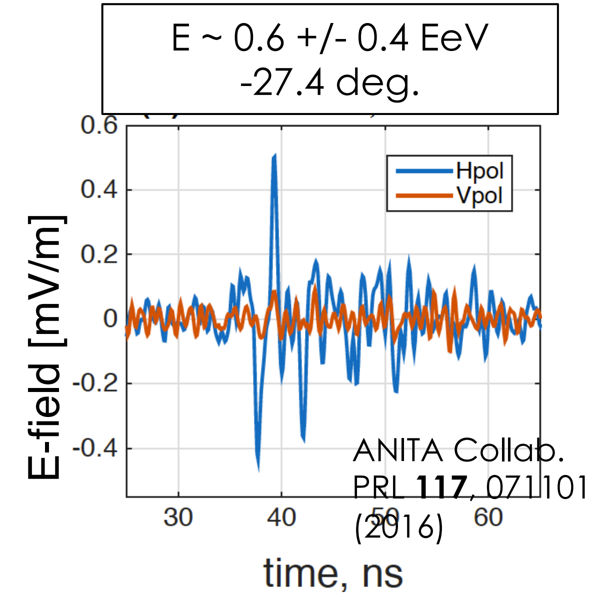
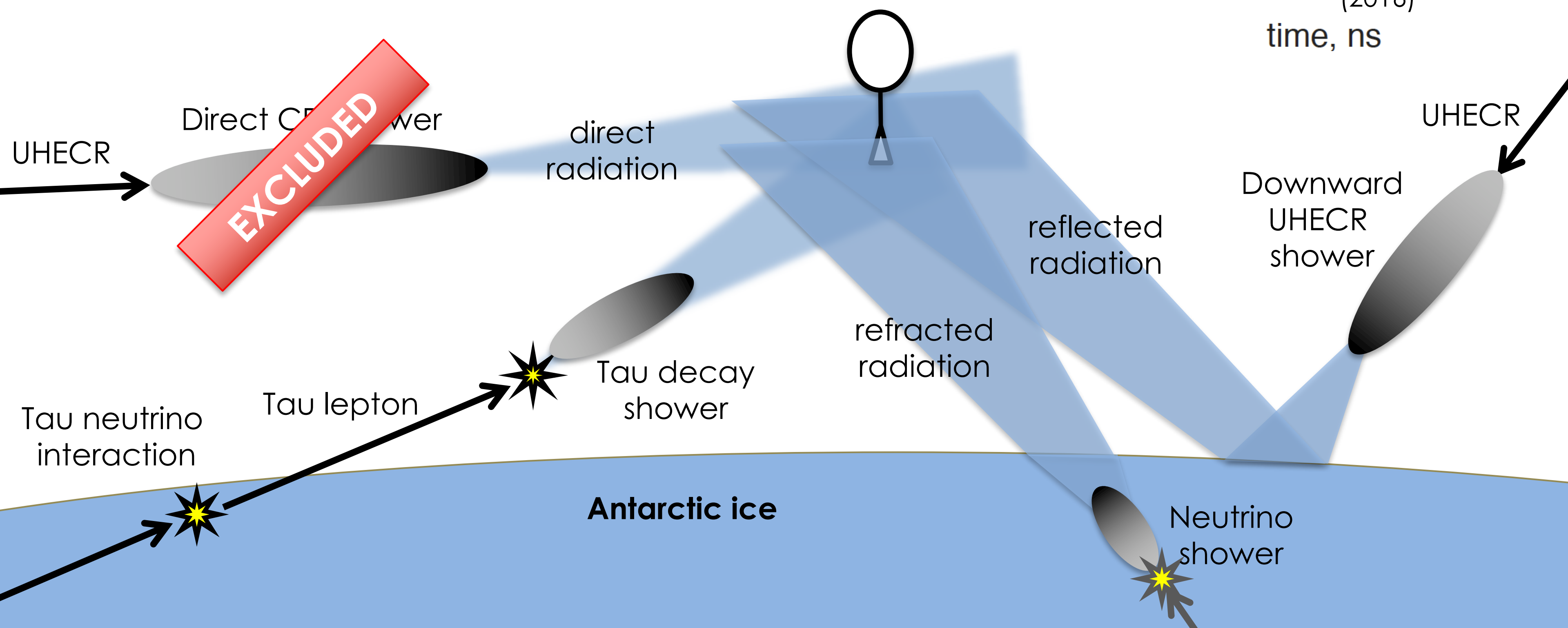
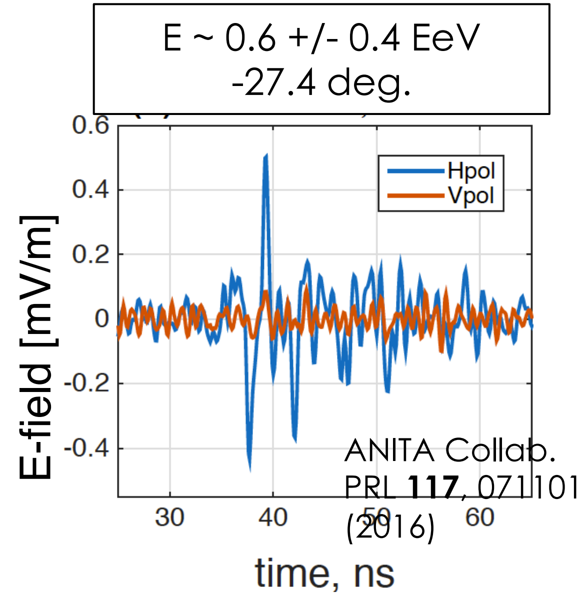
  - **“Direct” CR** atmospheric-skimming shower excluded

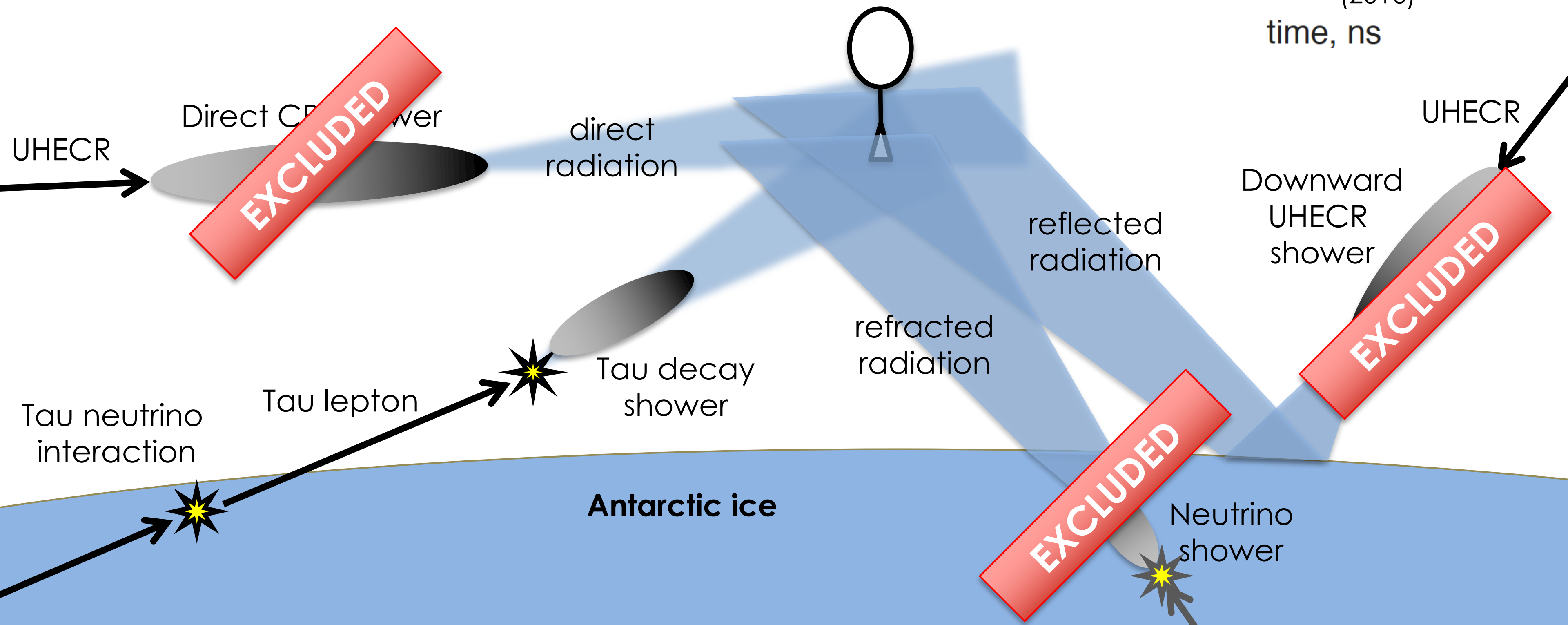




ANITA two upcoming events: are these tau neutrinos ??

- Arrived at payload **~27.4° & -35.0° below horizontal**
  - **"Direct" CR** atmospheric-skimming shower excluded
- Mostly **horizontally polarized**:
  - **Refracted radiation from ν-induced shower** IN ice excluded (vertical pol. expected).
  - **Reflected radiation from downward CR** shower excluded (inverted Hol pol. at reflection expected)



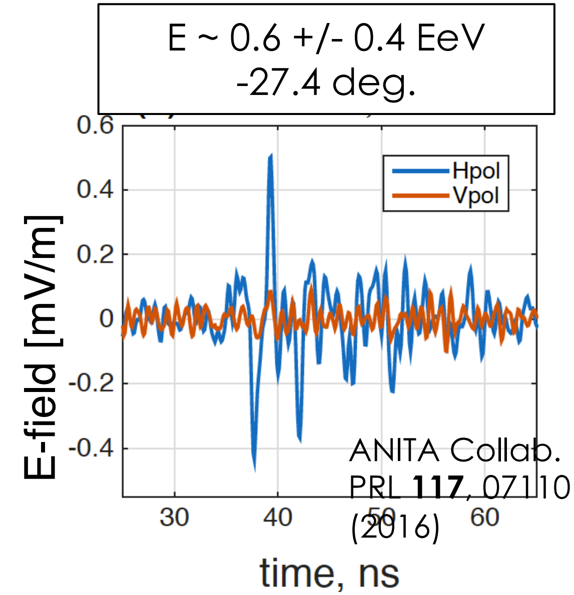


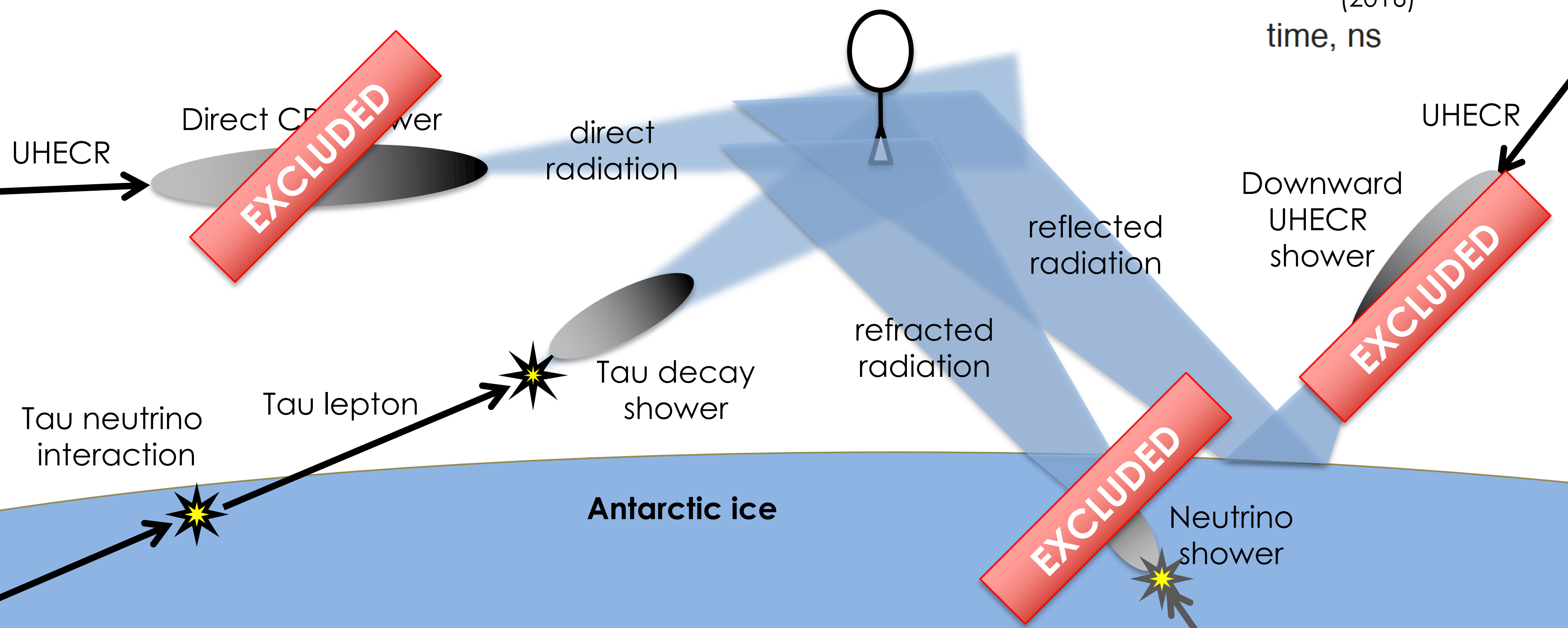
ANITA two upcoming events: are these tau neutrinos ??

BUT…

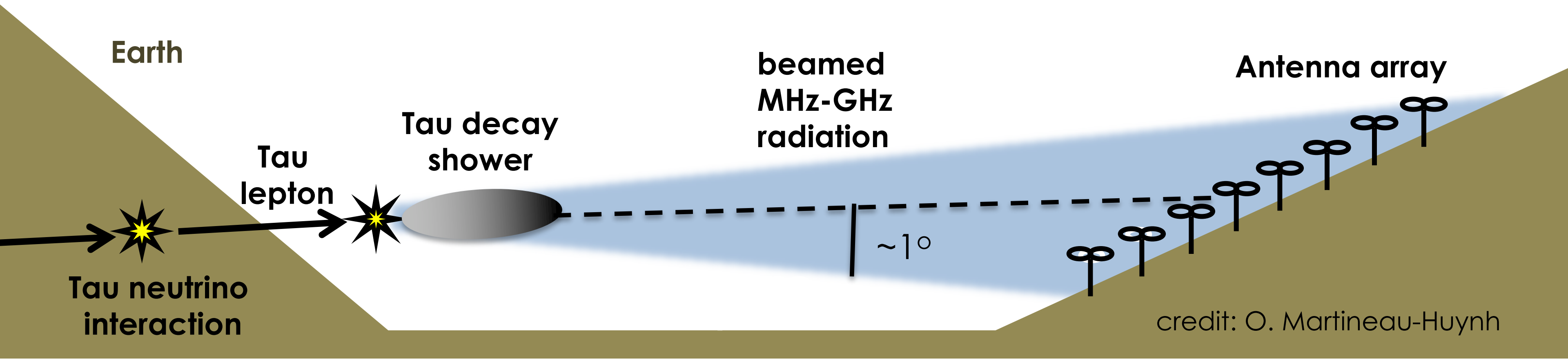
hypothesis of tau neutrino origin requires tau neutrino flux in strong tension with Auger & IceCube upper limits on neutrino flux.

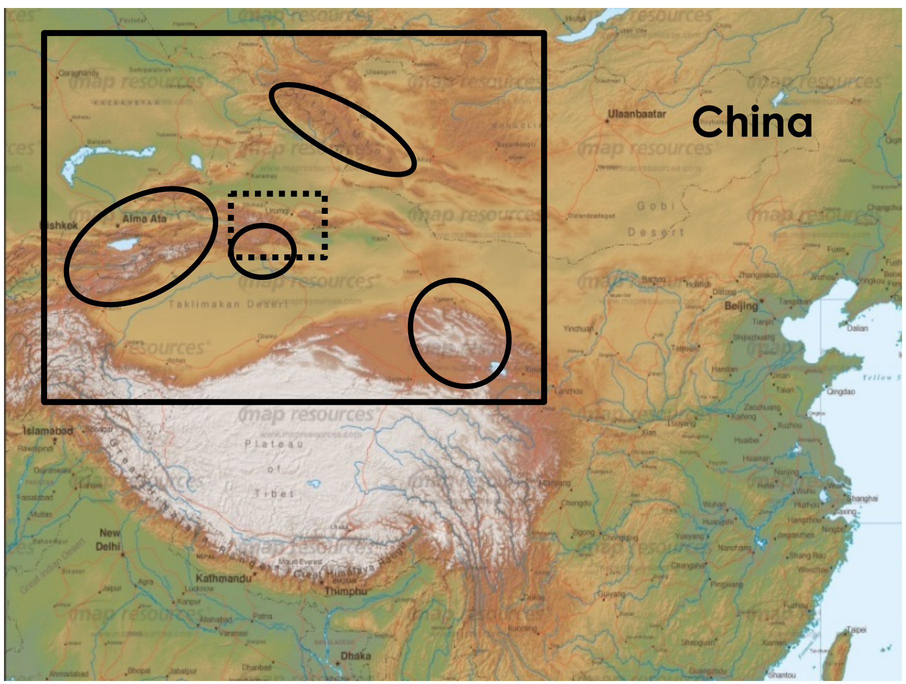
(A. Romero-Wolf et al., ICRC17; J.A-M et al. in preparation)





GRAND: Giant Radio Array for Neutrino Detection





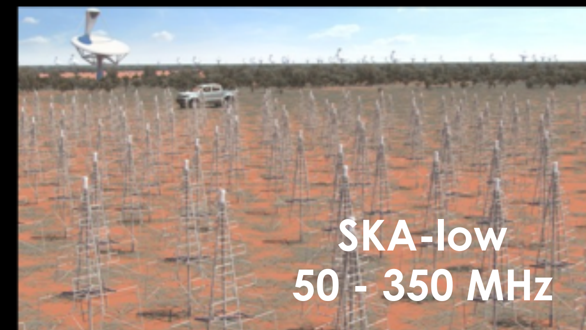
~ 200,000 self-triggering antenna array to be deployed over 200,000 km²

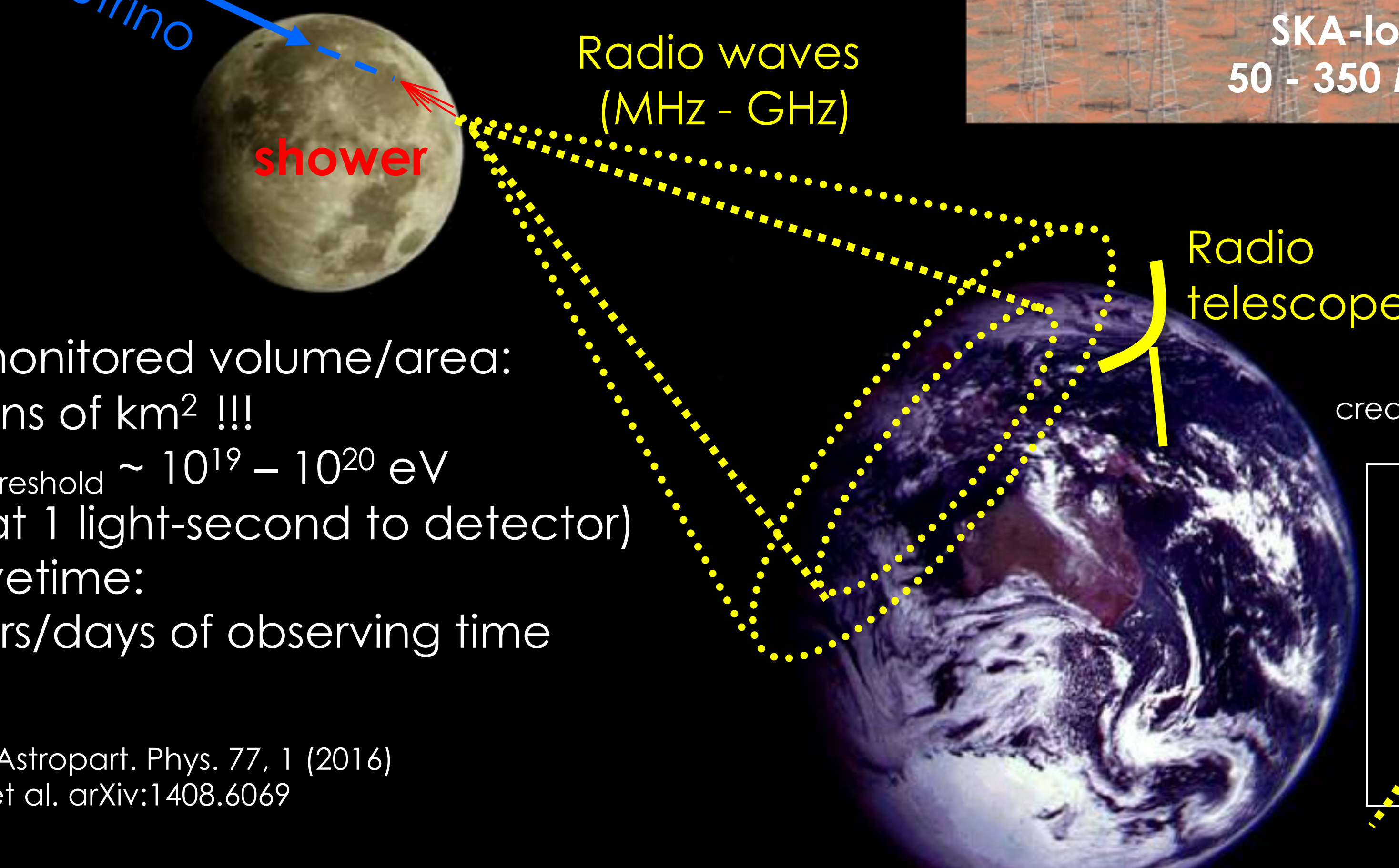
- Mountaineous site => enhance **Earth-Skimming ν_τ**
- Challenges: efficient noise rejection, deployment over vast area,...
- **GRANDproto35:**
  - 35 antennas
  - 24 scintillators (CR of E > 2 10^{17} eV)
- 300 antennas/300 km² engineering array in 2019

K. Fang, J. A-M et al. PoS (ICRC2017) 996; arXiv: 1708.05128 [astro-ph]. Whitepaper to appear soon.

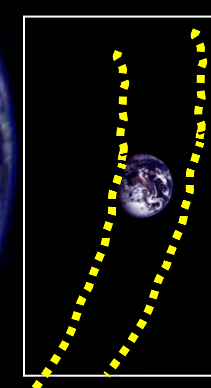
The Moon as a UHE neutrino detector

IGFAE involved in the High-Energy Cosmic Particles Focus group in SKA





credit: R. Ekers



- Huge monitored volume/area: millions of km^2 !!!
- High $E_{threshold}$ ~ 10^{19} – 10^{20} eV (showers at 1 light-second to detector)
- Small livetime: a few hours/days of observing time

J.D. Bray, Astropart. Phys. 77, 1 (2016)
J.D. Bray et al. arXiv:1408.6069

Conclusions & Outlook

- Radio detection has evolved from a promising technique to a **real alternative for UHECR & neutrino detection.**

- Wide range of experiments in dense media and in the atmosphere already working and in the planning stage.

- Expertise of simulations of radio emission in IGFAE is well-exploited in many of these experiments and in the design of future ones.

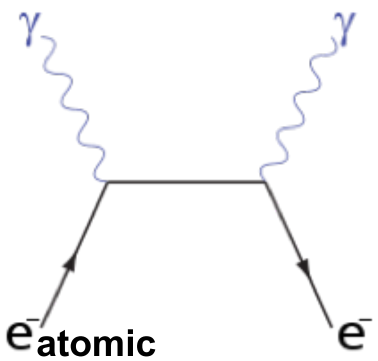
Backup

The Askaryan effect

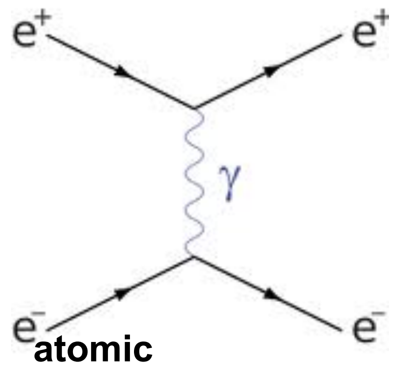
– “Entrainment” of electrons from medium as shower evolves.

Due to MeV photons & electrons interacting through:

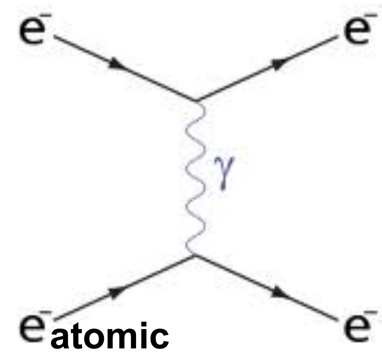
G. Askar´yan, Soviet Phys. JETP **14**, 441 (1962)



Compton



Bhabha



Moeller

+ positron annhilation

– As a consequence **an excess of electrons over positrons develops in the shower**:

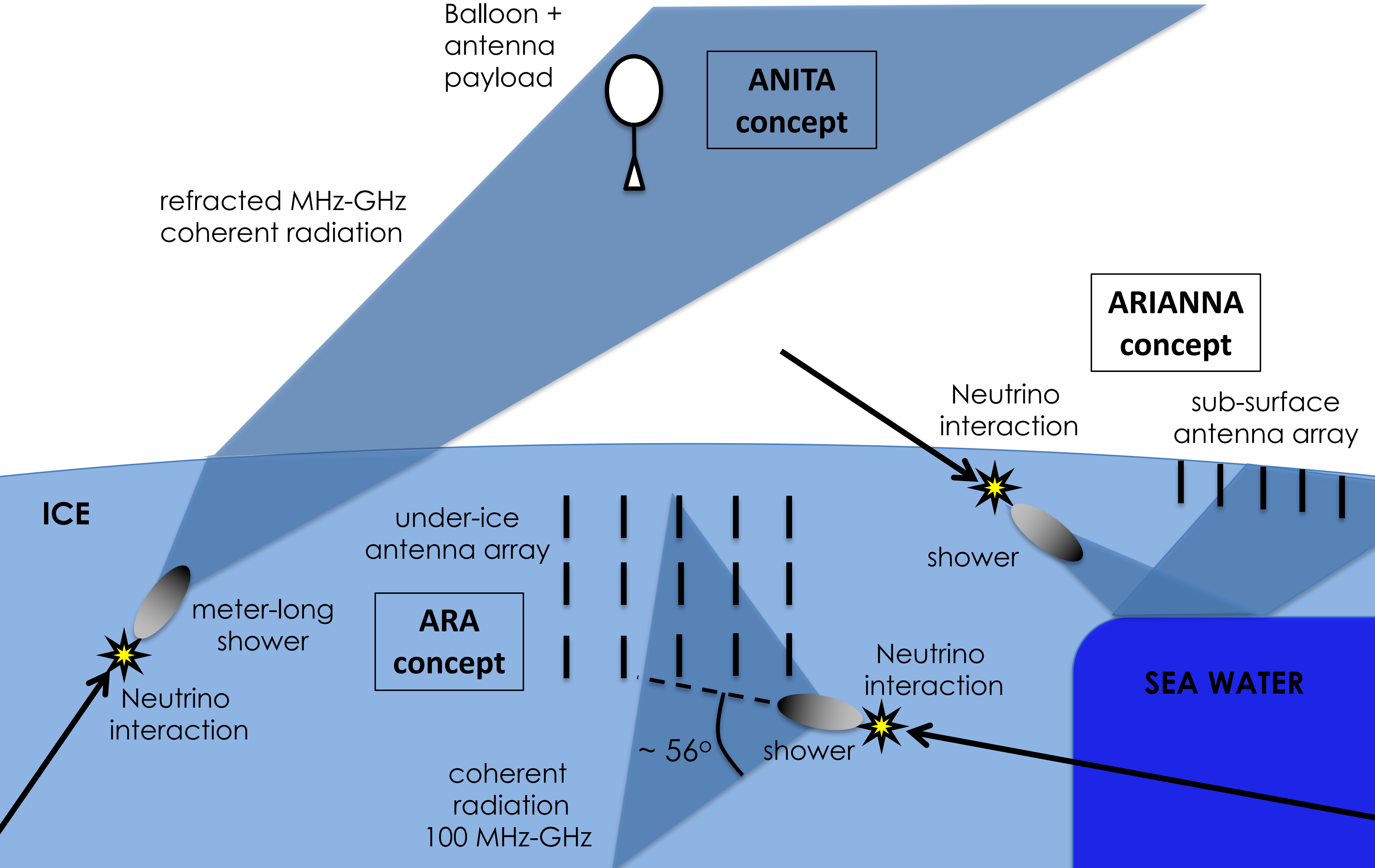
$$\Delta q = \frac{N(e^-) - N(e^+)}{N(e^-) + N(e^+)} \approx 25\%$$

G.A. Askaryan

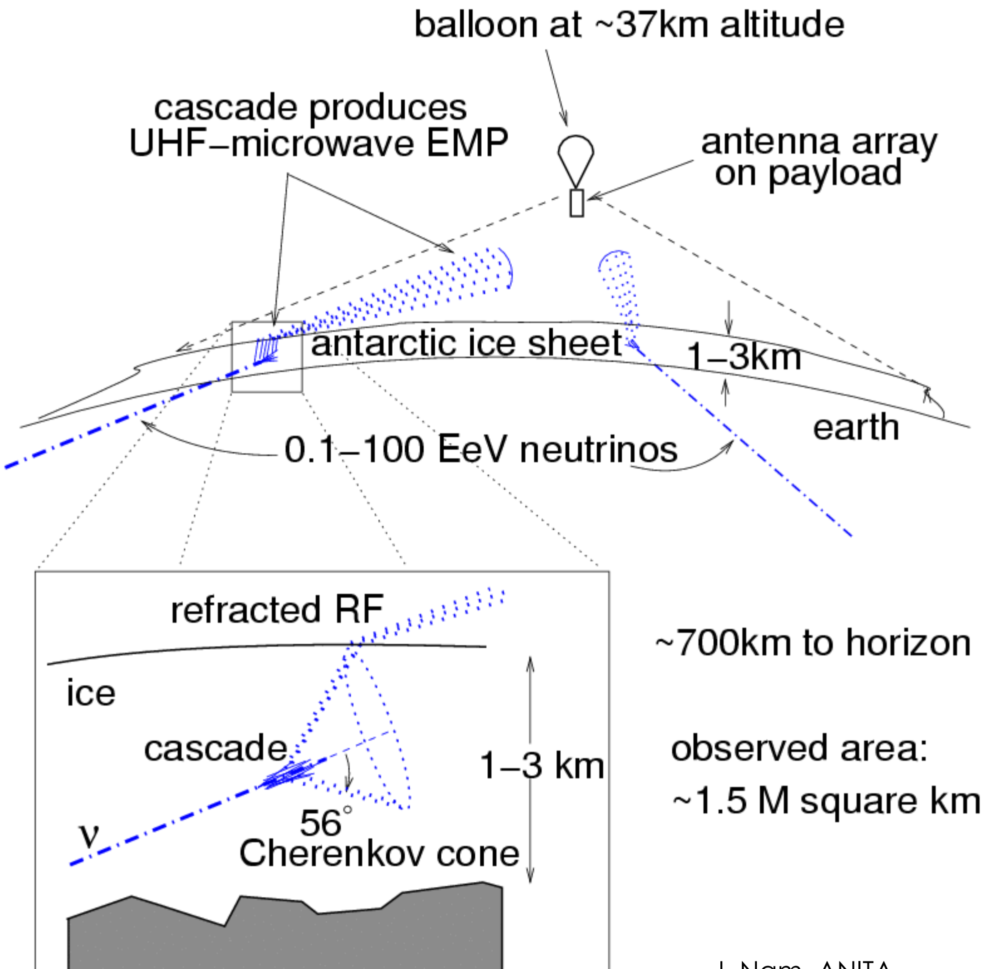
– Excess develops in any medium with bound electrons.

Effect confirmed in beam experiments at SLAC - D. Saltzberg et al. PRL **86** (2001)

The radio technique in dense media



ANITA-I, II, III & IV



J. Nam, ANITA Collab. ICRC 2017

NASA Long Duration Balloon flights

~ 37 km altitude over Antarctica carrying antenna payload: 200 – 1200 MHz

- Large ice volume monitored:

$V_{eff}\,\Omega \sim 2 \times 10^4\ km^3\ sr$ @ 10^{18} eV

- Relatively small livetime: ~ 1 month
- Relatively large $E_{threshold} > 10^{18}$ eV

(showers at ~100 km distance)

4 ANITA flights:

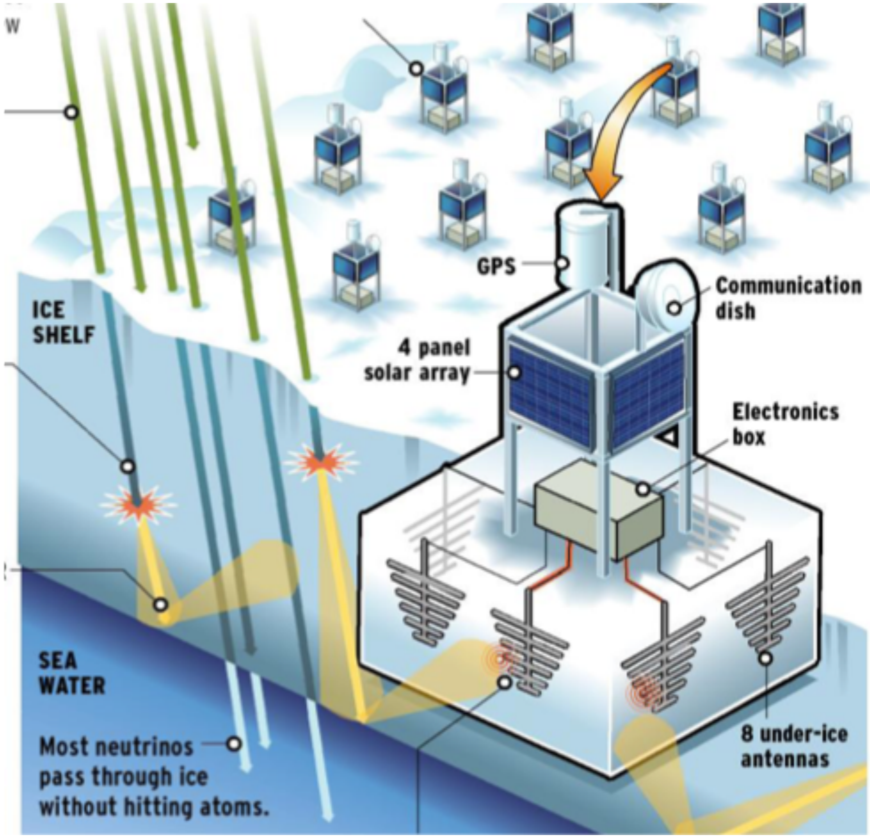
ANITA-I: 2006/07 – 0 ν, 16 UHECR detected

ANITA-II: 2008/09 – 0 ν, 1 UHECR, 1 intriguing evt.

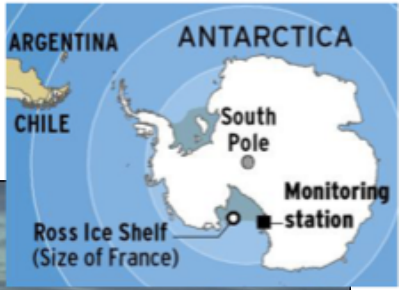
ANITA-III & IV: 2014/15 & 16/17 – analysis on-going

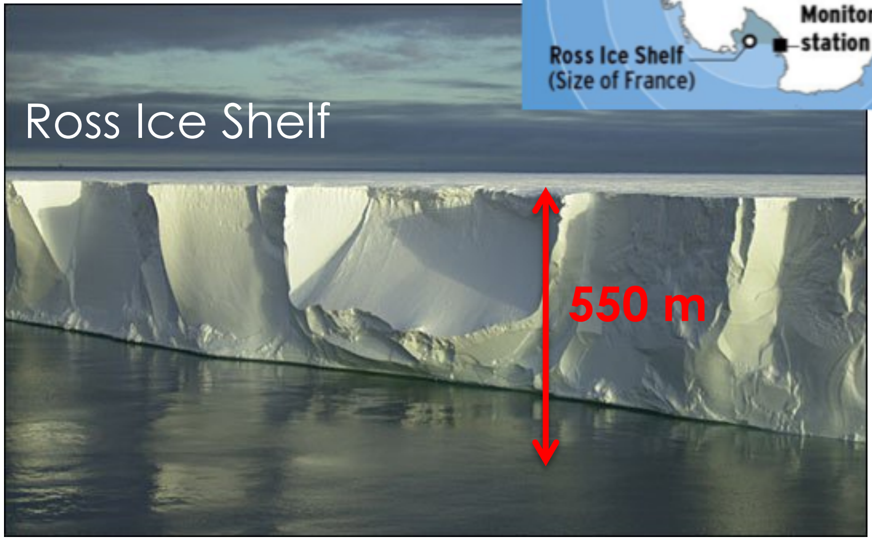
3.6 x sensitivity of ANITAIII, 20% smaller threshold.

ANITA II - best limit at E > 3 10^{19} eV



ARIANNA

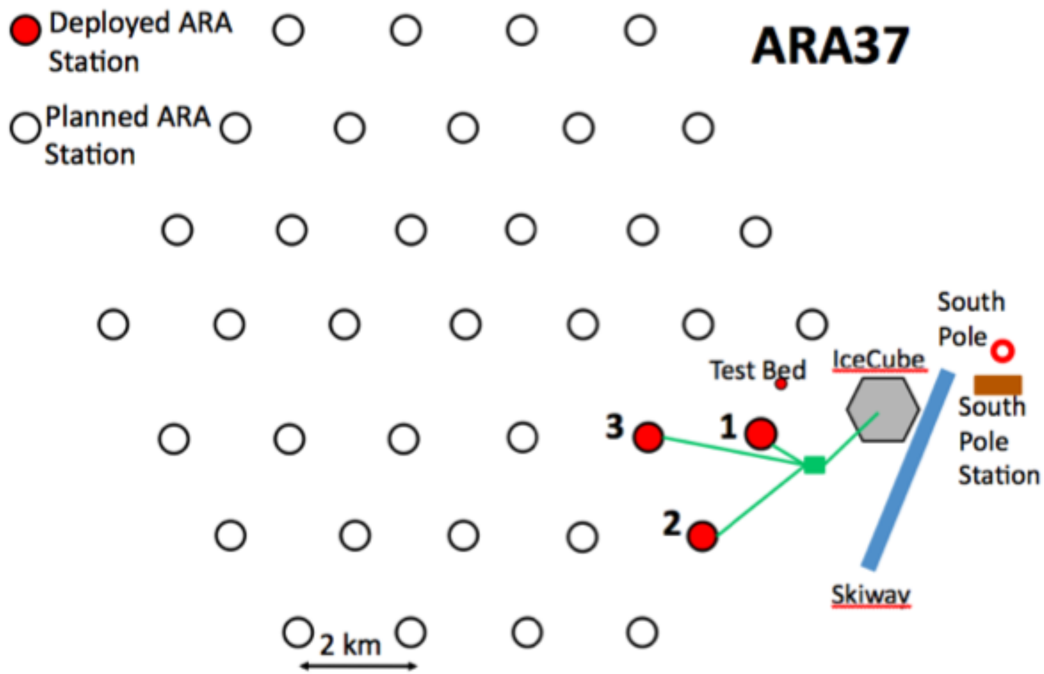




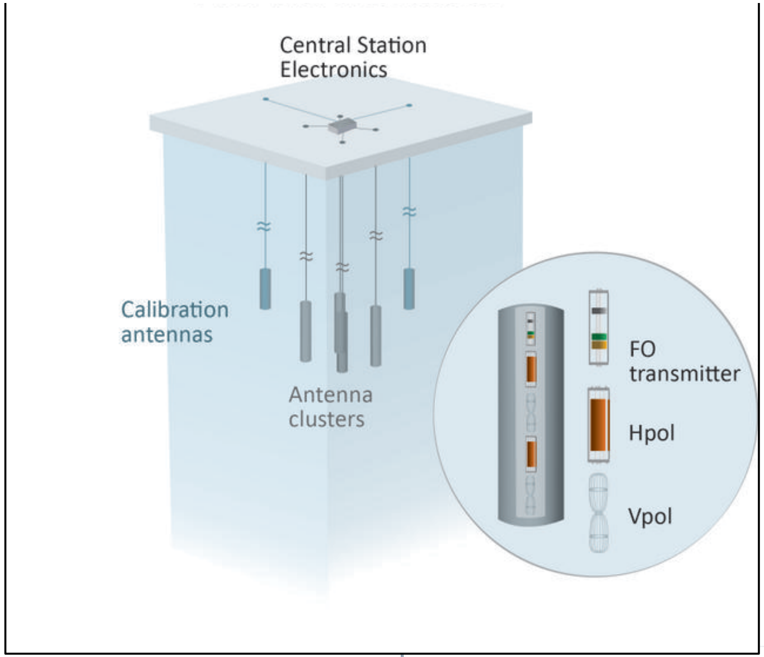
Ground-based 1296-antenna array 10^3 km^2 buried just below surface of Ross Ice Shelf

- 4 LPDA antennas/station: 80 MHz – 1.3 GHz
- $E_{threshold}$ ~ 10^{17} eV, $V_{eff}\,\Omega$ ~ 450 km^3 sr @ 10^{18} eV
- long livetime: ~ several years
- **Prototype Hexagonal Radio Array (7 stations) working reliably for the last 2 years.**
- data from 3 station in 10 months => 1st limits

ARIANNA Coll. Astroparticle Phys. **70**, 12 (2015)
S.Barwick, ICRC 2017



ARA: Askaryan Radio Array



ARA37-station antenna array covering ~100 km^2 buried 200 m below surface at South Pole

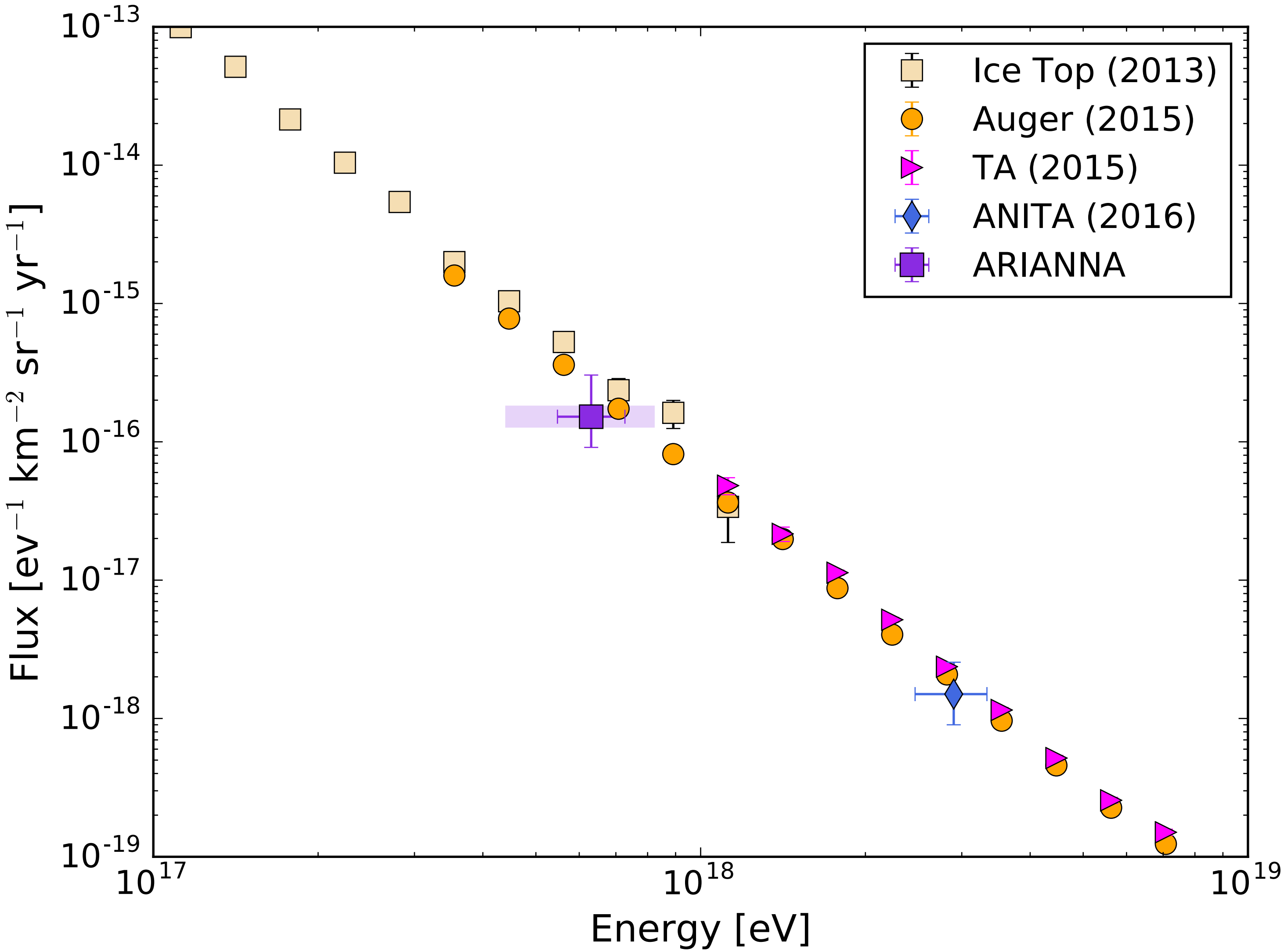
- 8 HPol + 8 Vpol ant./station: 150 – 800 MHz
- E_{thresh} ~ 5 x 10^{16} eV, V_{eff} Ω ~ 200 km^3 sr @ 10^{18} eV
- long livetime ~ several years
- **3 stations deployed – 3 more in 2017/18** (including a phased array to lower threshold)
- data from TestBed prototype: no ν candidates => 1st limits

V Pol Antennas | H Pol Antennas

ARA & ARIANNA: studying ice properties

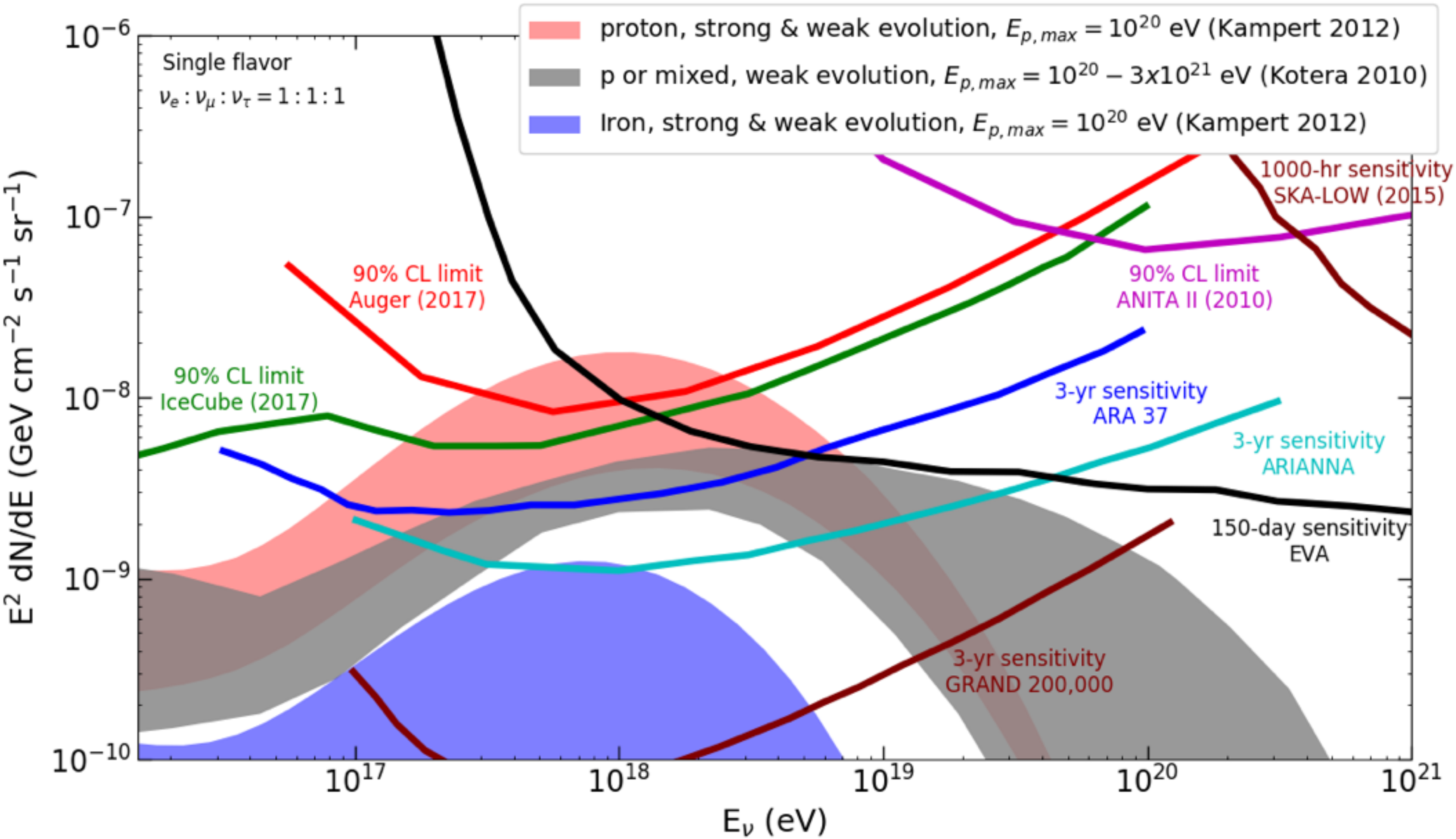
ARA Collab. Astroparticle Phys. **35**, 457 (2012), Astroparticle Phys. **70**, 62 (2015).
M. Lu, ICRC17. A. Vieregg, ICRC17, J. Kelley ICRC17

UHECR spectrum with radio: ANITA & ARIANNA



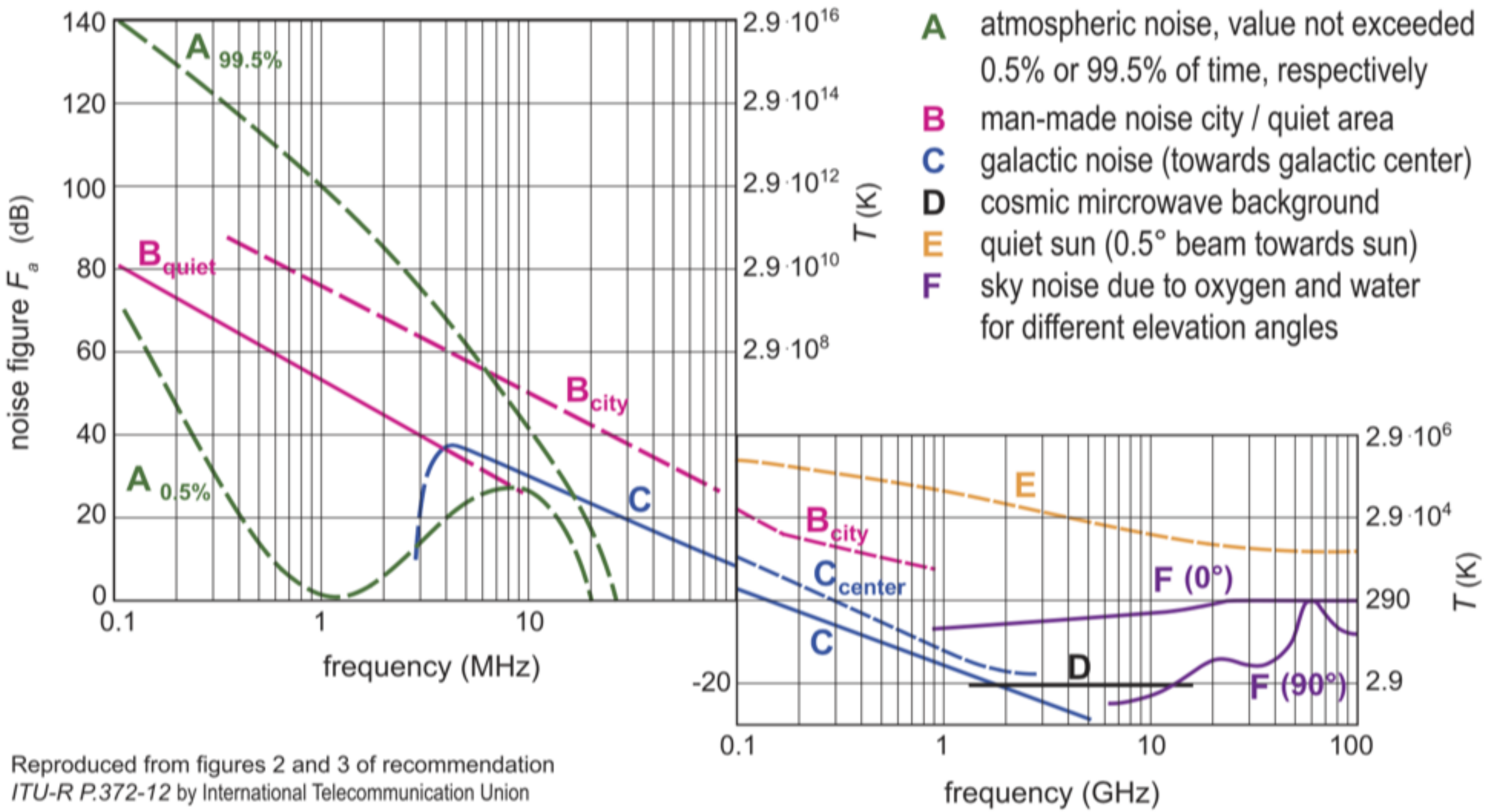
from review T. Huege, D.Z. Besson, Prog. Exp. Theor. Phys. in press. arXiv:1701.02987

Square-Kilometer-Array projected sensitivity



NOTE: All limits & models per flavor. Differential ones converted to 1 decade in log10(E)

Background noise



Reproduced from figures 2 and 3 of recommendation *ITU-R P.372-12* by International Telecommunication Union

Detecting UHEν (& CRs) with SKA (Square Kilometer Array)

- world's largest radio telescope
  - 1 km^2 of total collecting area
  - thousands of antennas
  - to be built in Australia & South Africa
- broad scientific goals: astronomical & cosmological obs.

- "phased array": observe multiple regions of sky simultaneously
- large livetime for Moon observ.