Giant Radio Array for Neutrino Detection

GRAND

Science and Design

Presented by Sijbrand de Jong
Based on the GRAND white paper in preparation

Content:
- Science Case and Observational Status
- GRAND Proposal: Design & Performance
- Stages of realisation
- Summary and Outlook

Science Case

- The Highest Energy Particles in the Universe:
  - Astronomical:
    - Where are they produced ?
    - How are they produced ?
    - How do they propagate from the source to us ?
  - Particle Physics:
    - How do they interact ?
    - What is produced in their collisions ?
      - (while propagating through space or when hitting the Earth's atmosphere)

Science Case

What are they ?

- The Highest Energy Particles in the Universe:
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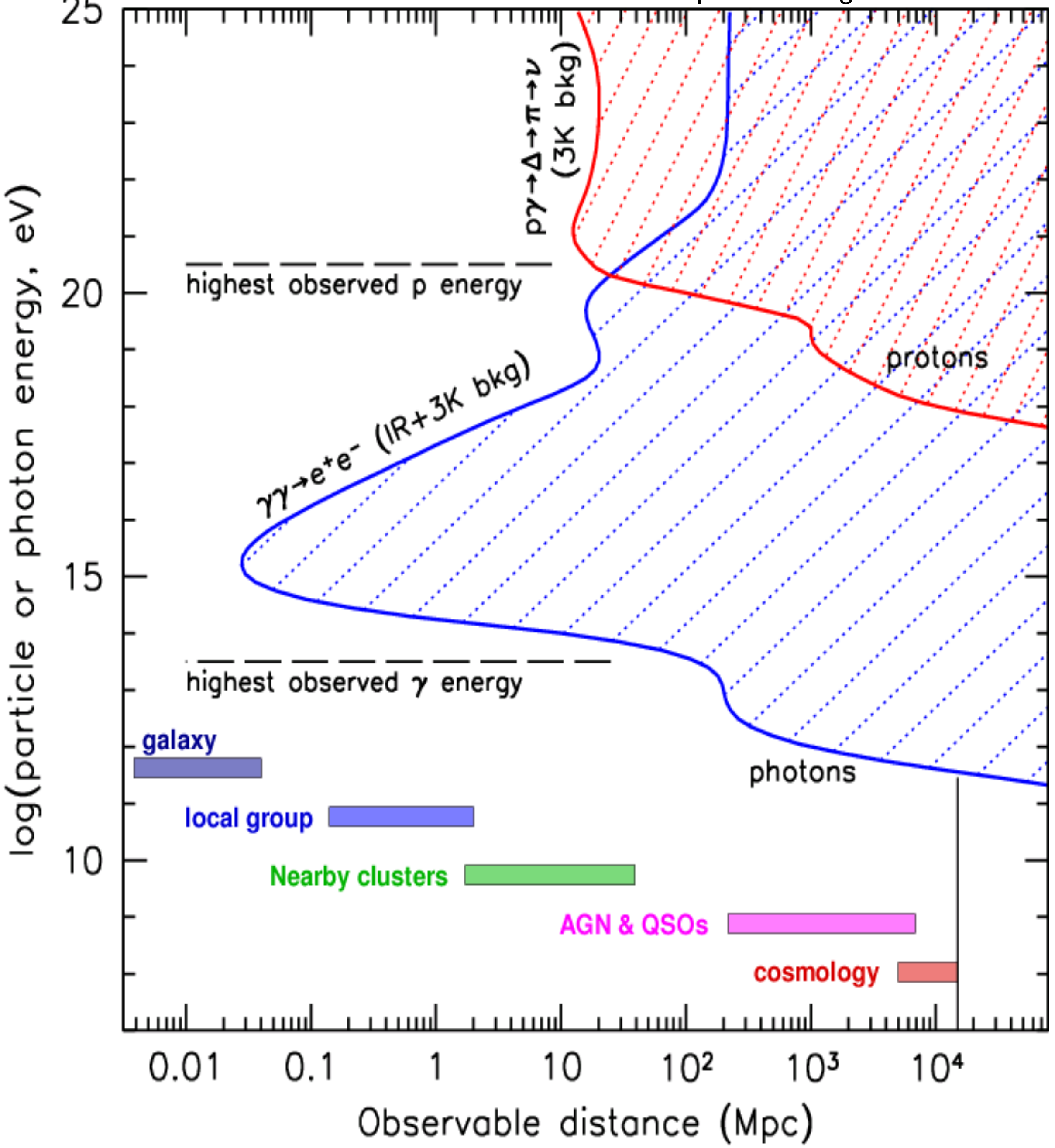
Science Case

Most promising to point back to their source (at highest E):

1. Neutrinos
2. Photons
3. Protons
4. …

https://arxiv.org/abs/0812.3809

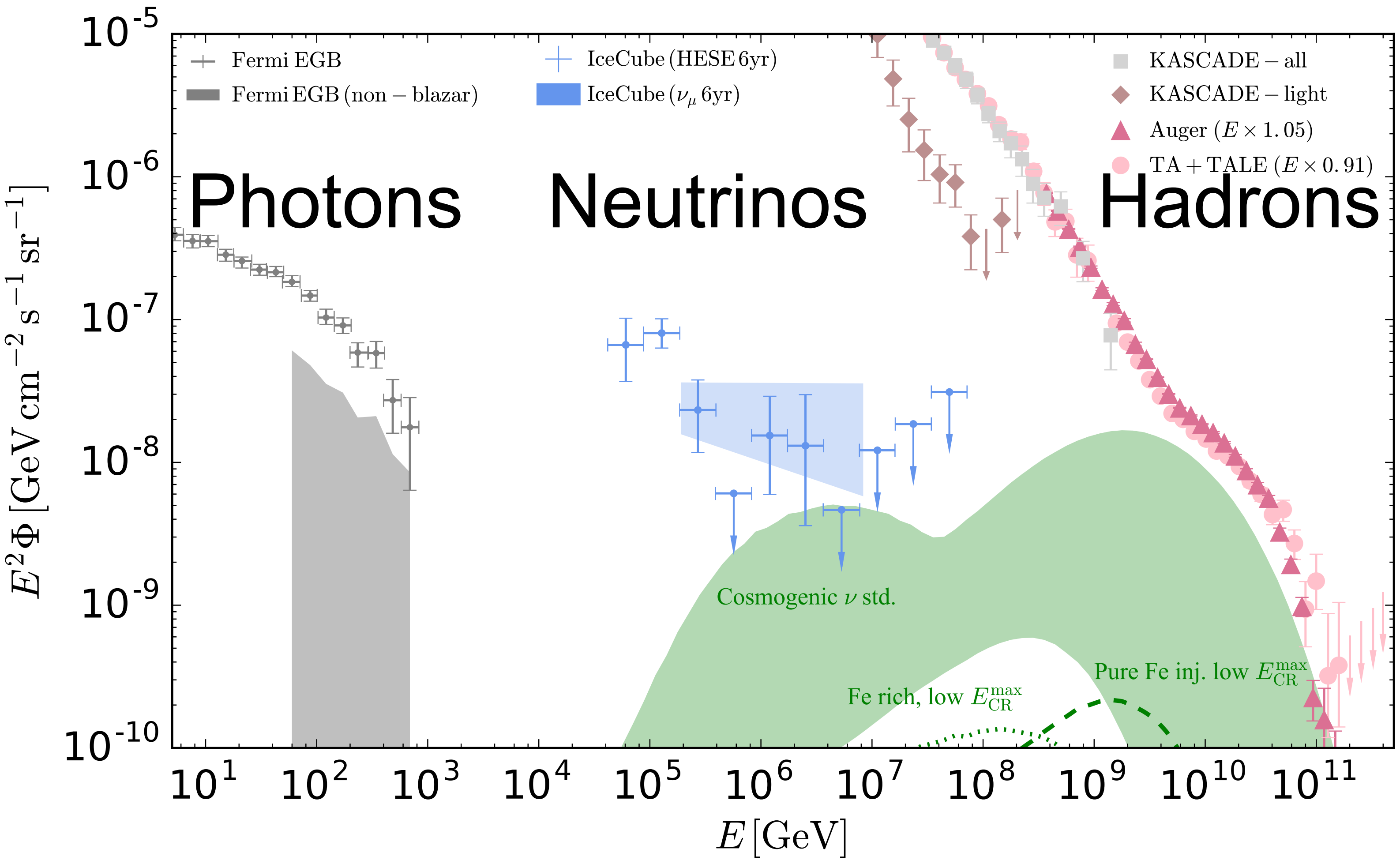


Science Case

- Sources of Cosmic Neutrinos
  - Point sources:
    - Any place where ultra-high-energy hadrons are around
    - Waxman-Bahcall limit (Mannheim, Protheroe, Rachen)
    - Rate depends on cosmic ray rate (~known) and source conditions & cosmic evolution (interesting)
  - Cosmogenic
    - Photo-disintegration (GZK,…)
    - Guaranteed flux
    - Rate and energy distribution depend on cosmic ray spectrum and composition (interesting)

Science Case

- Cosmic Neutrinos Observational Status

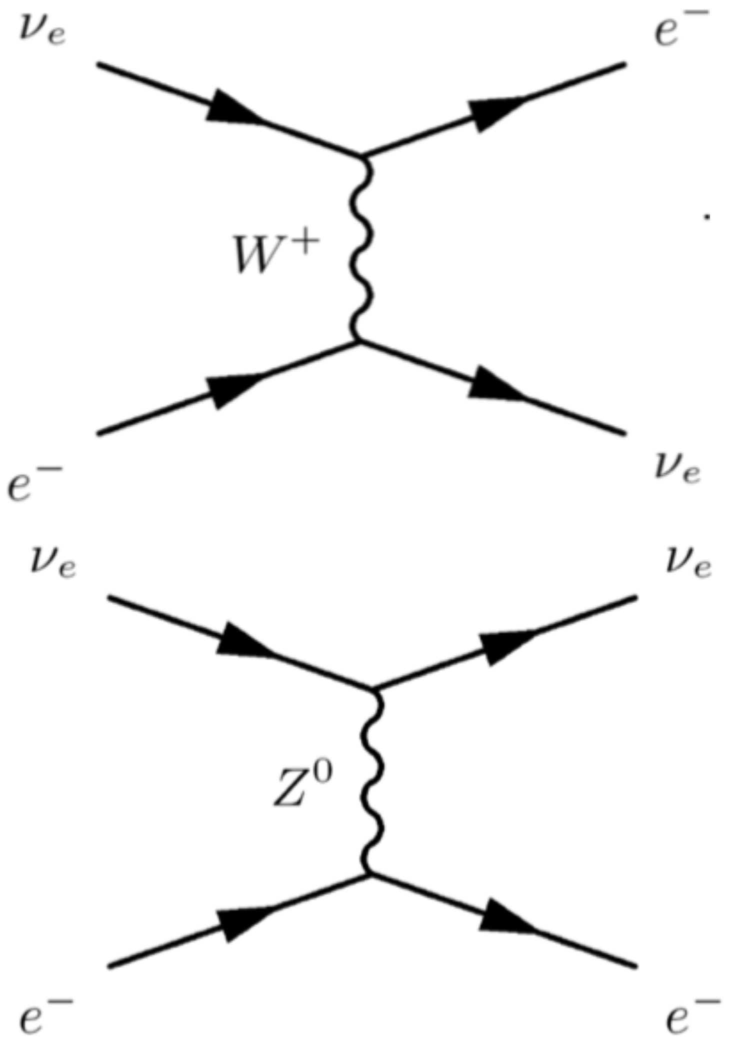


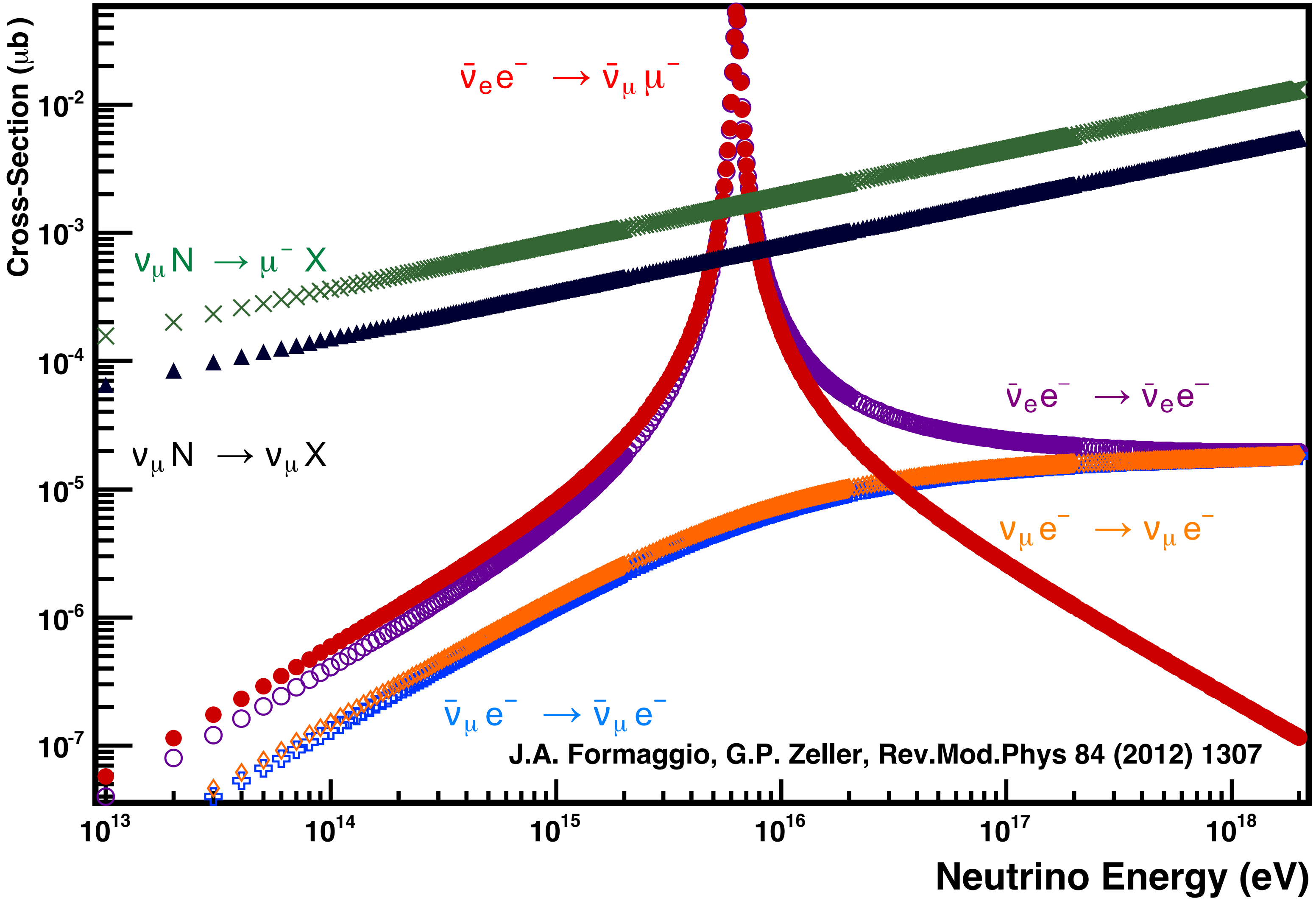
Science Case

- Finding the Sources of Ultra-High-Energy Cosmic Rays
  - Protons:
    - Exposure large enough ?
    - Particle ID good enough ?
    - Source(s) sufficiently near
  - Photons:
    - Source(s) sufficiently close ?
    - Particle ID good enough ?
  - Neutrinos:
    - Low cross section with matter !
    - Detection efficiency and exposure large enough ?

Ultra-High-Energy Neutrino Detection

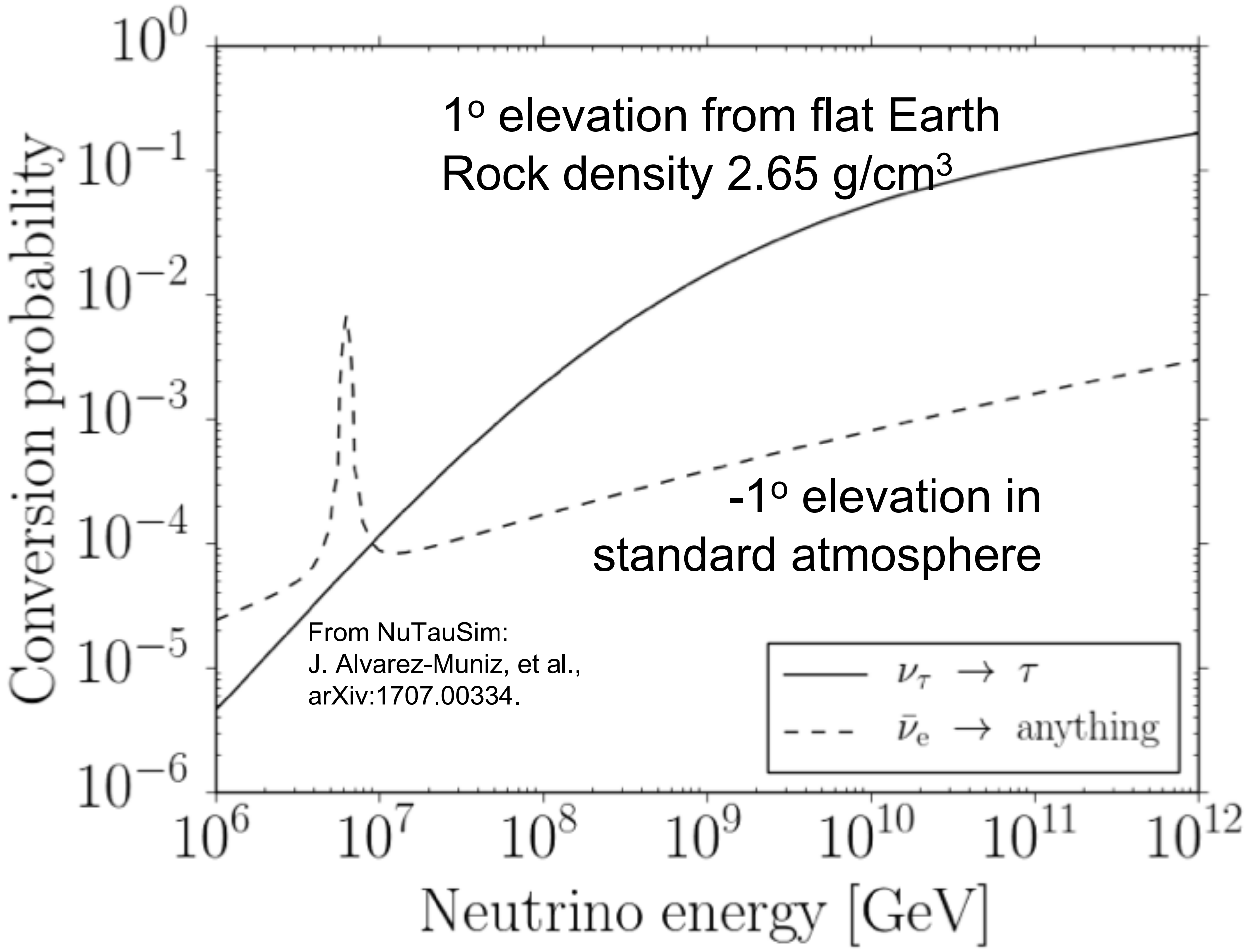
- The Cross-Section helps !





Ultra-High-Energy Neutrino Detection

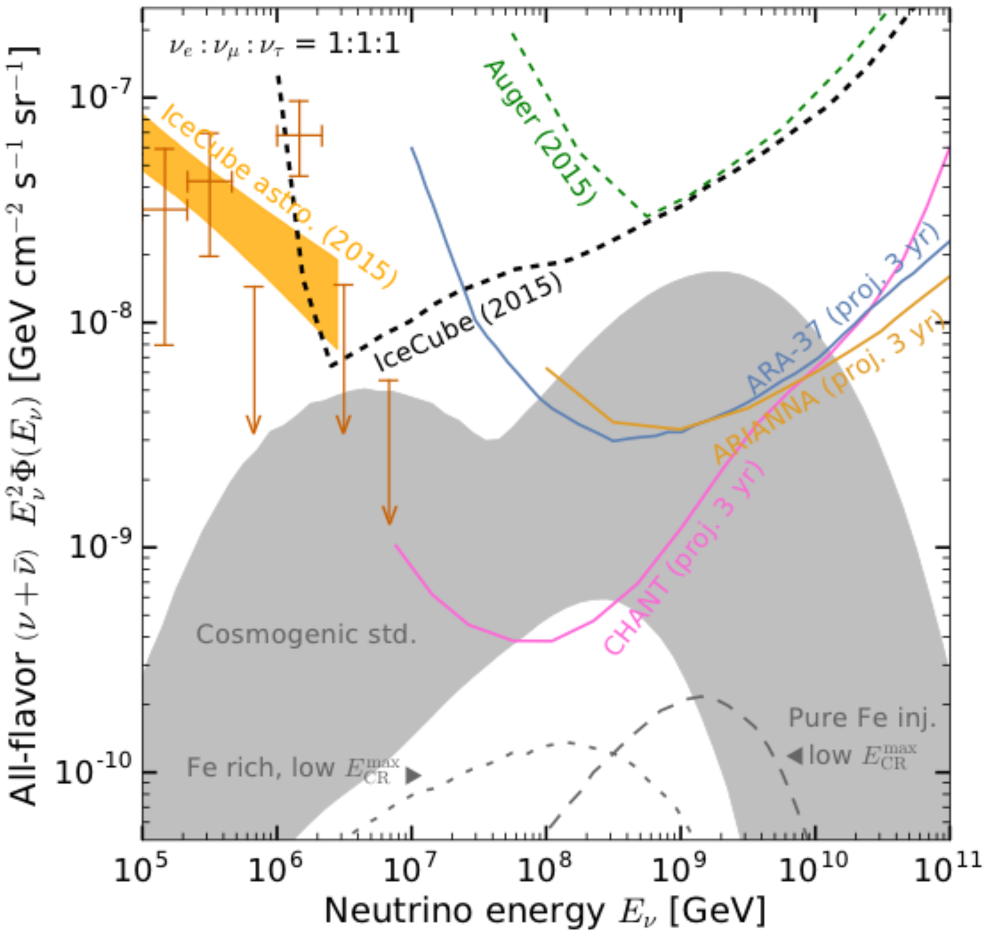
- Conversion rate in
  - Earth crust: high
    Charged lepton interacts in rock
  - Mountains: high
    Fair escape probability for τ and μ
    μ stable and hard to detect
  - Atmosphere: low
  - Go for: **mountains** and ν_τ



Ultra-High-Energy Neutrino Detection

- Detection Strategies
  - Neutrinos towards Ultra-High-Energy:
    - Flux goes down:
      large exposure in km^2sr required
      - At highest energy for cosmogenic neutrinos:
        few 100 000 km^2sr for few events
    - Cross-section goes up:
      depth of target can become less
      - Make detectors large area and
        relatively shallow ("2-D" instead of "3-D")

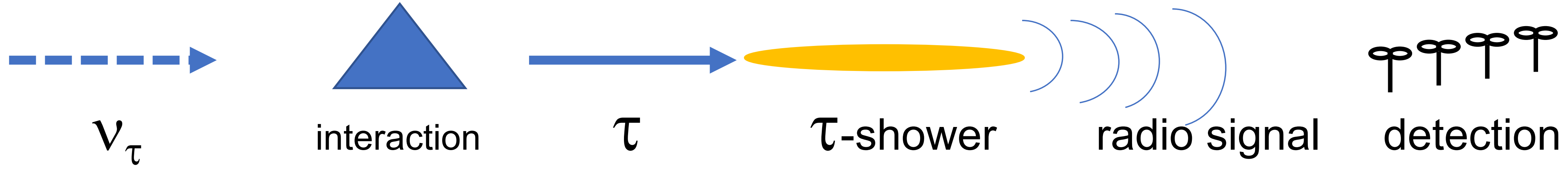
Status



Giant Radio Array for Neutrino Detection

- Tau neutrino interaction in mountain

  (and Earth crust and atmosphere)
- Use large radio frequency detection array to detect particle shower(s) from interaction
  - Aim at 200 000 km^2
  - Low noise environment
  - Cost effective
  - Optimise for horizontal showers
- Aim primarily for tau neutrinos



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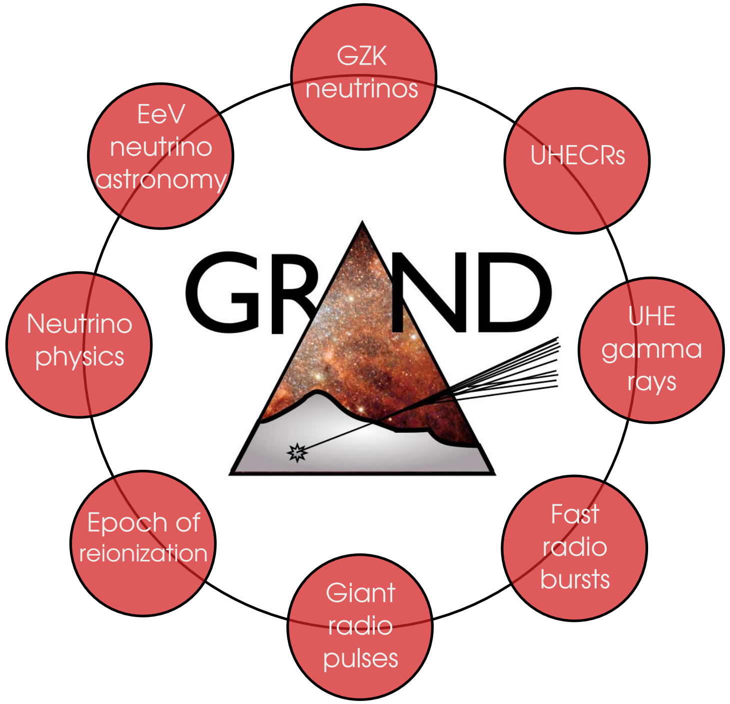
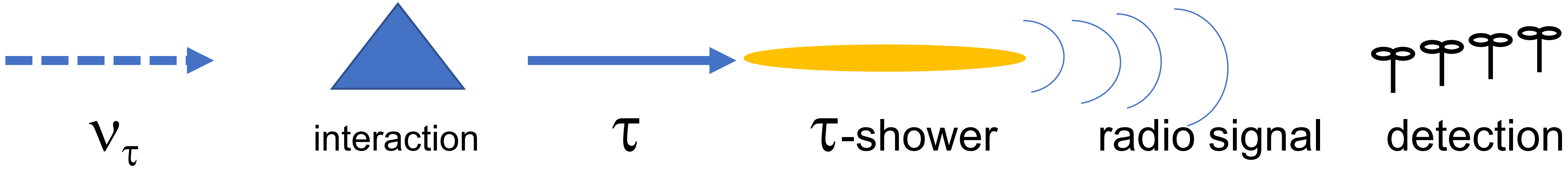


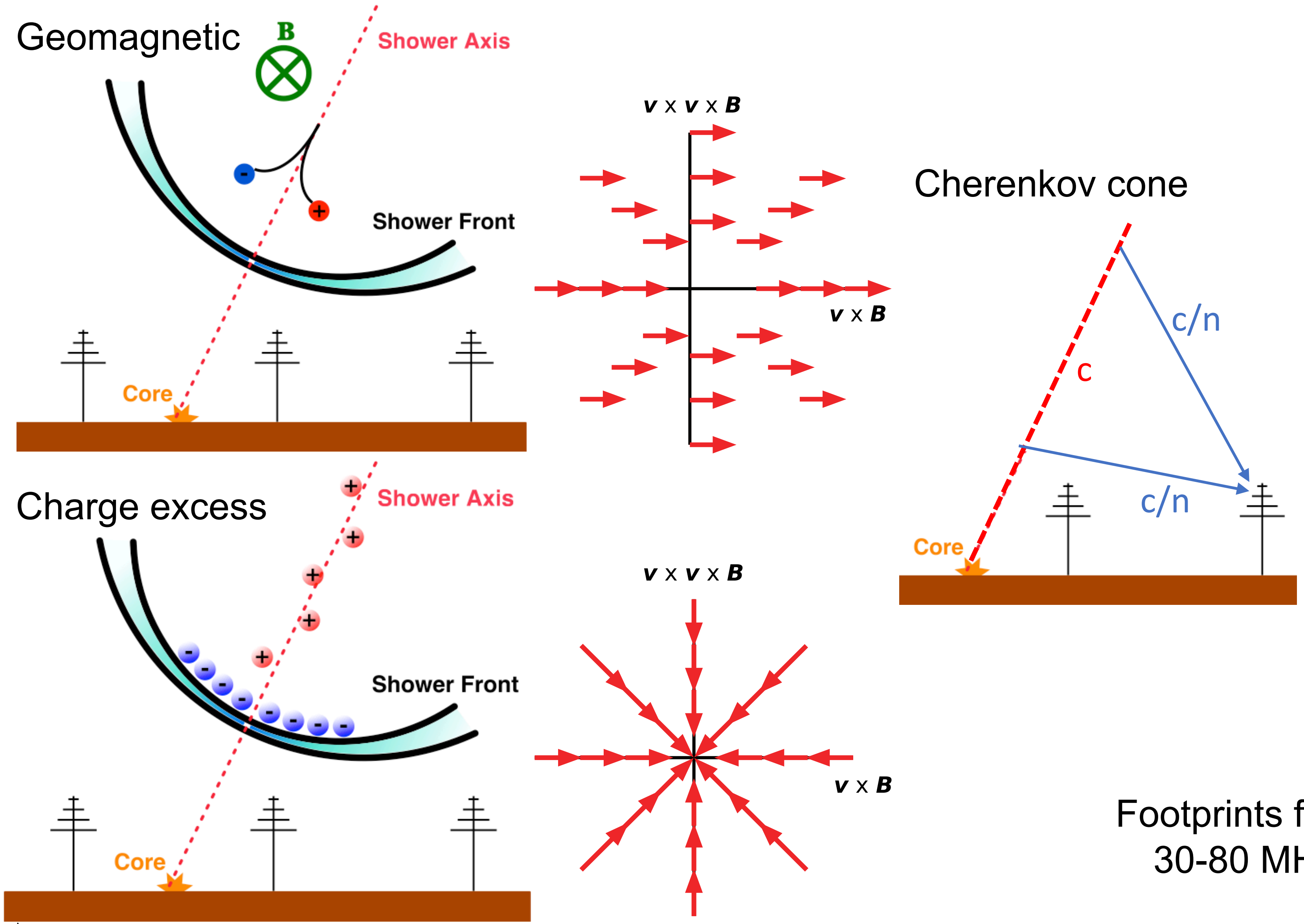


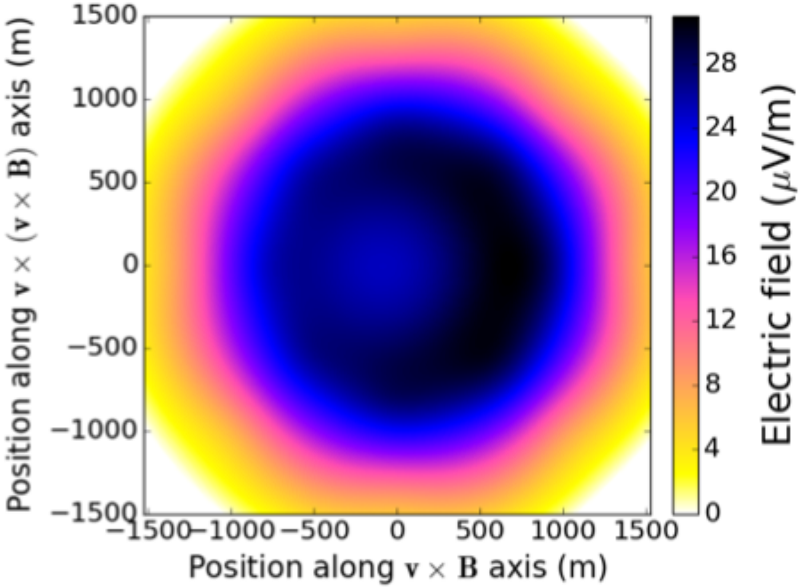
GRAND: Giant Radio Array for Neutrino Detection

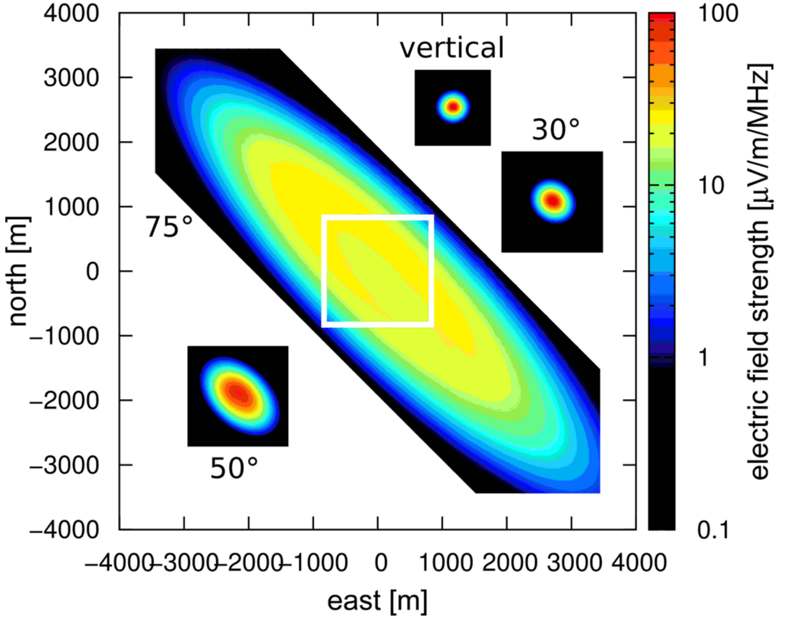
- Note: this is one of a number of strategies

  Alternatives:
  - Satellite fluorescence telescope (JEM-EUSO, CHANT, POEMMA,…)
  - Balloon flight radio detection (ANITA, EVA,…)
  - Radio detection in ice (ARA, ARIANNA,…)
  - Lunar skimming events (LUNASKA, NuMoon, RESUN, SKA,…)
  - …

Radio frequency emission of air showers

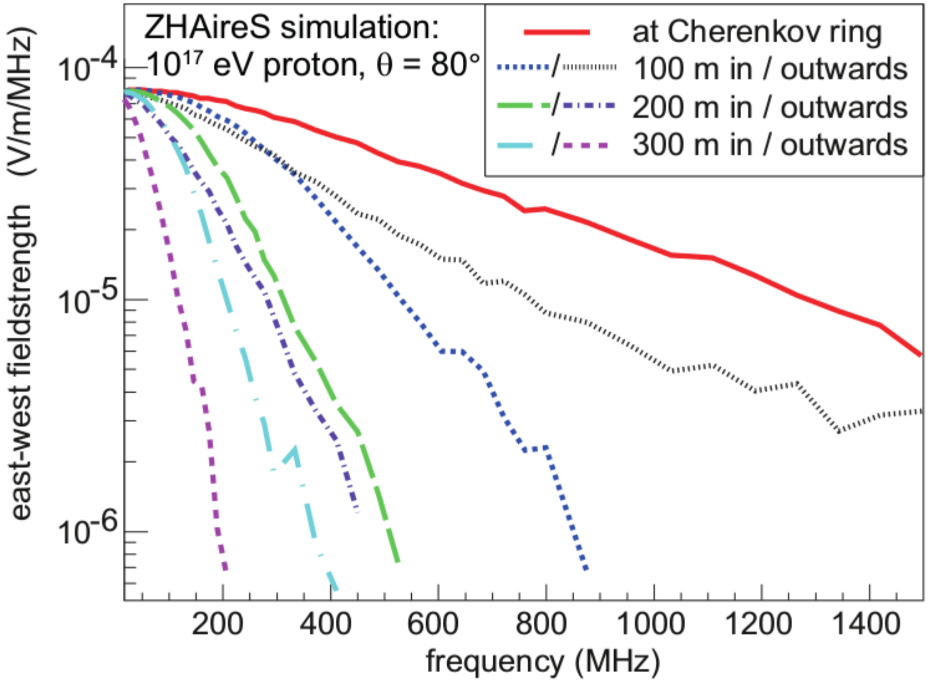


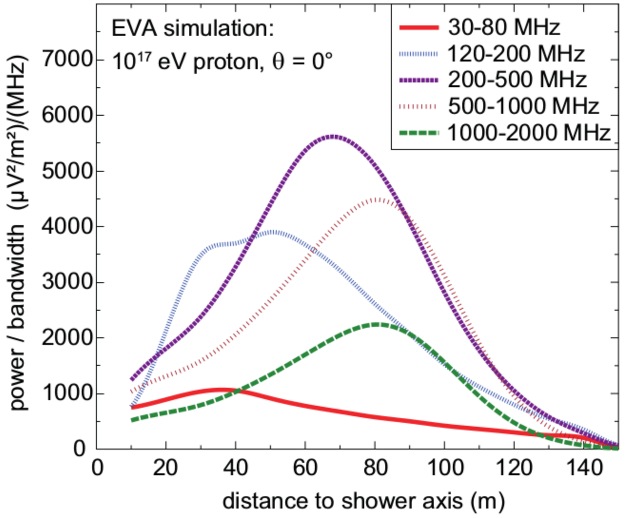


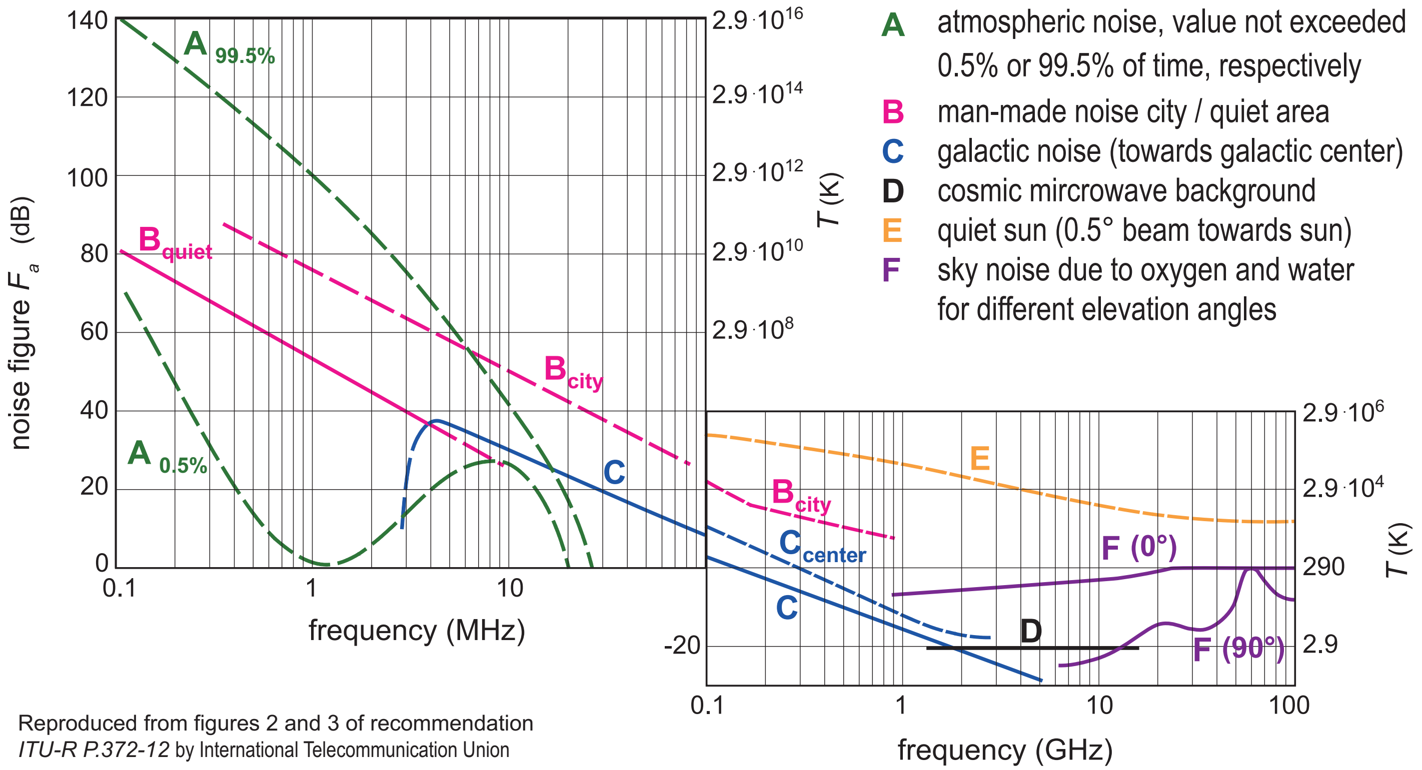


Footprints for 30-80 MHz

Radio frequency emission of air showers







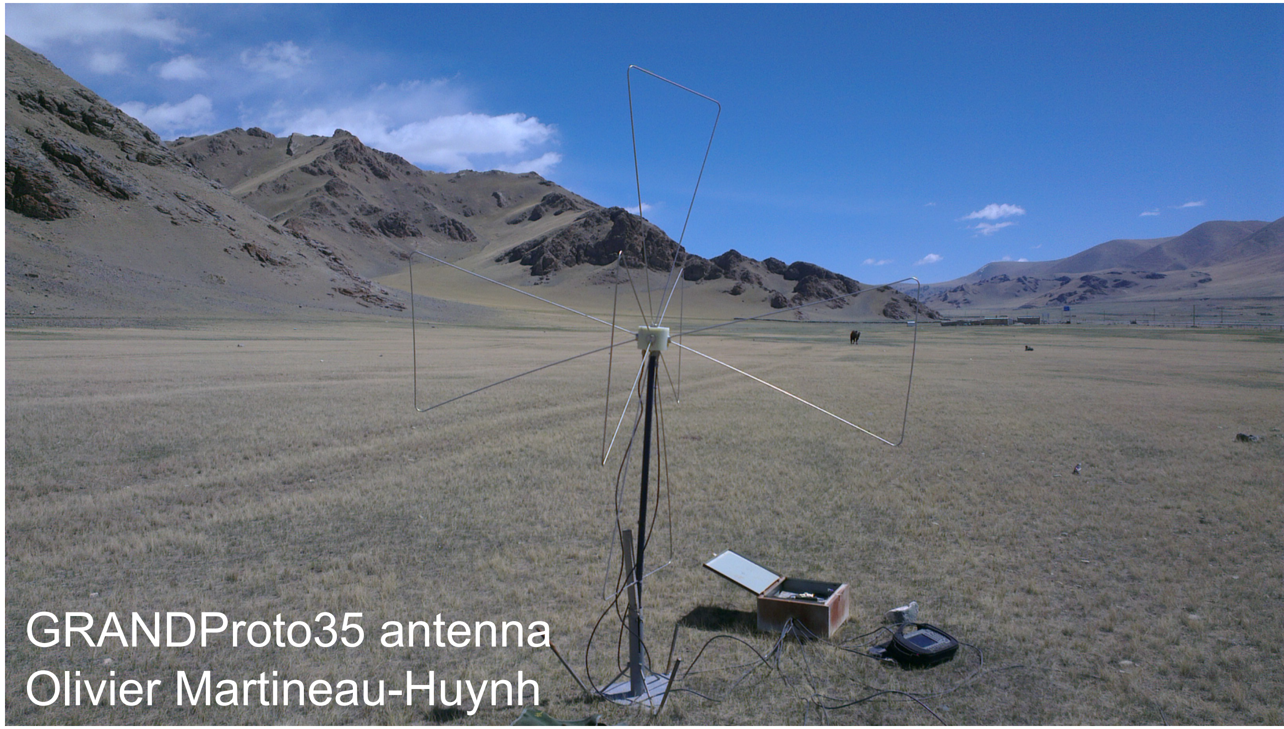
Reproduced from figures 2 and 3 of recommendation *ITU-R P.372-12* by International Telecommunication Union

GRAND: 50 MHz —— 200 MHz

Background noise — technology/ price driven

Radio detection of air showers

- Previous experience from:
  - LOPES, CODALEMA,…
  - LOFAR, AERA, TUNKA-REX,…
  - TREND
- Can measure:
  - Energy (established, being improved)
  - Direction (established)
  - Composition (established, being improved)
- Issues to solve:
  - Fully efficient autonomous trigger from detector itself (self-trigger)
  - Make it cheaper, aim for 500 €
  - Make it more reliable, easier to mass deploy, …



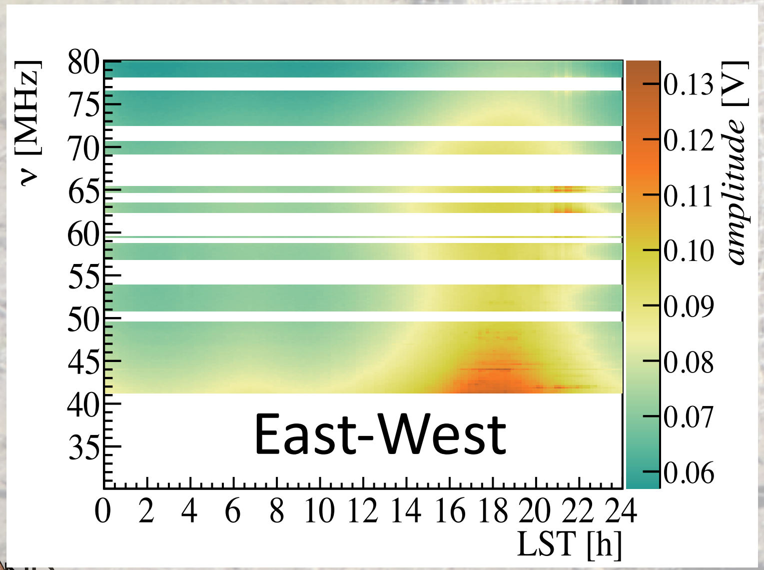
GRANDProto35 antenna
Olivier Martineau-Huynh

Radio detection of air showers: experience - AERA

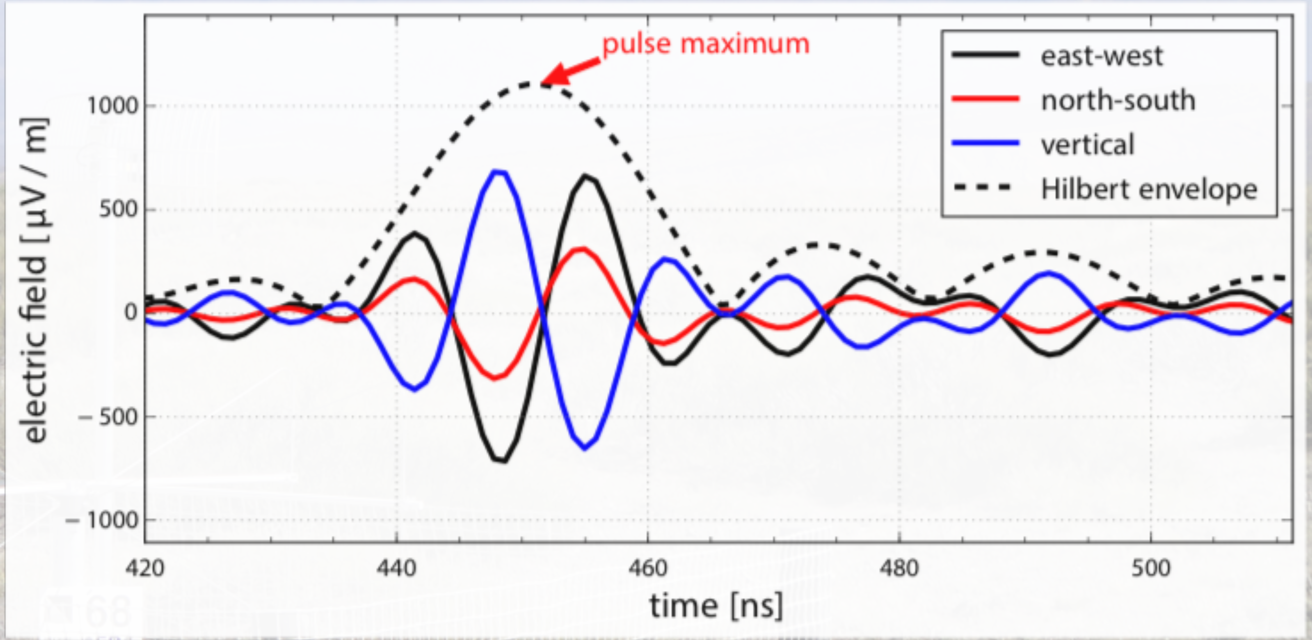
Calibration:

$$U_{\substack{\text{North-South}\\ \text{East-West}}} = \vec{\vec{H}}_{\substack{\text{North-South}\\ \text{East-West}}} \vec{E}$$

- Calculation/simulation
- Octocopter calibration
- Galactic center calibration



Signal treatment



(Absolute) 30-80 MHz radio energy density:

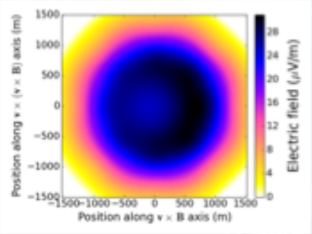
$$\varepsilon = \varepsilon_0 c \left[\sum_{t_i=t_1}^{t_2} \left|\vec{E}(t_i)\right|^2 \Delta t - \frac{t_4 - t_3}{t_2 - t_1} \sum_{t_i=t_3}^{t_4} \left|\vec{E}(t_i)\right|^2 \Delta t \right] \text{eV/m}^2$$

signal region — background region

Radio detection of air showers: Emission mechanisms

Geomagnetic — Charge asymmetry

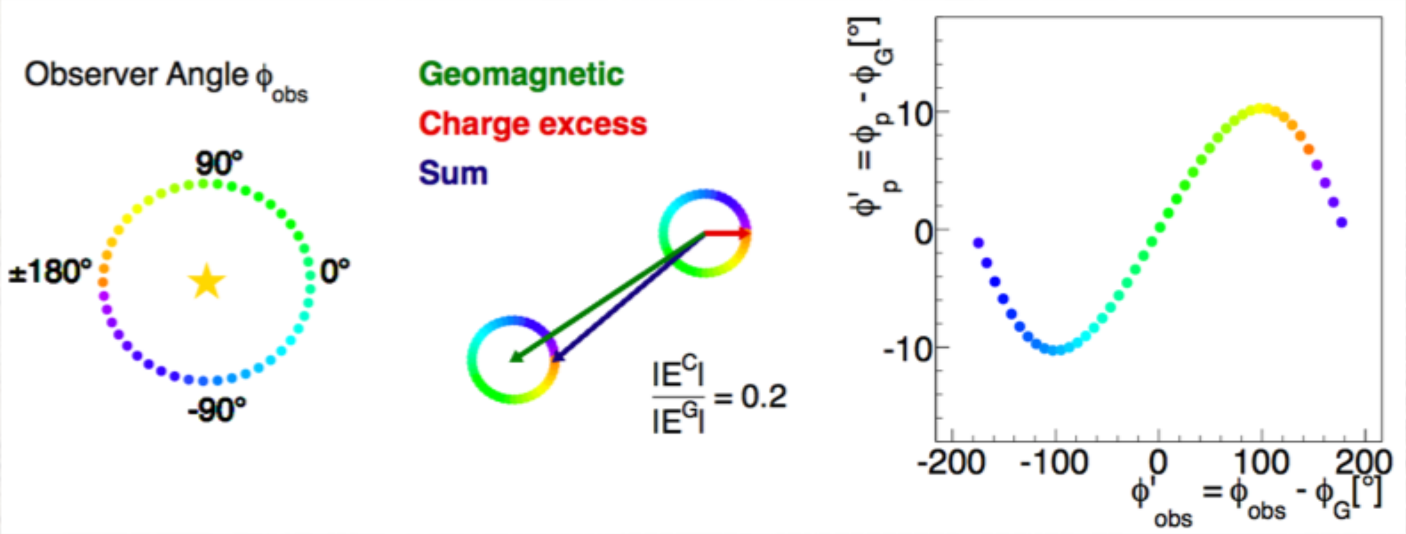
$$\vec{E} = \vec{E}^G + \vec{E}^C = |E^G|\vec{e}^{\,G} + |E^C|\vec{e}^{\,C}$$

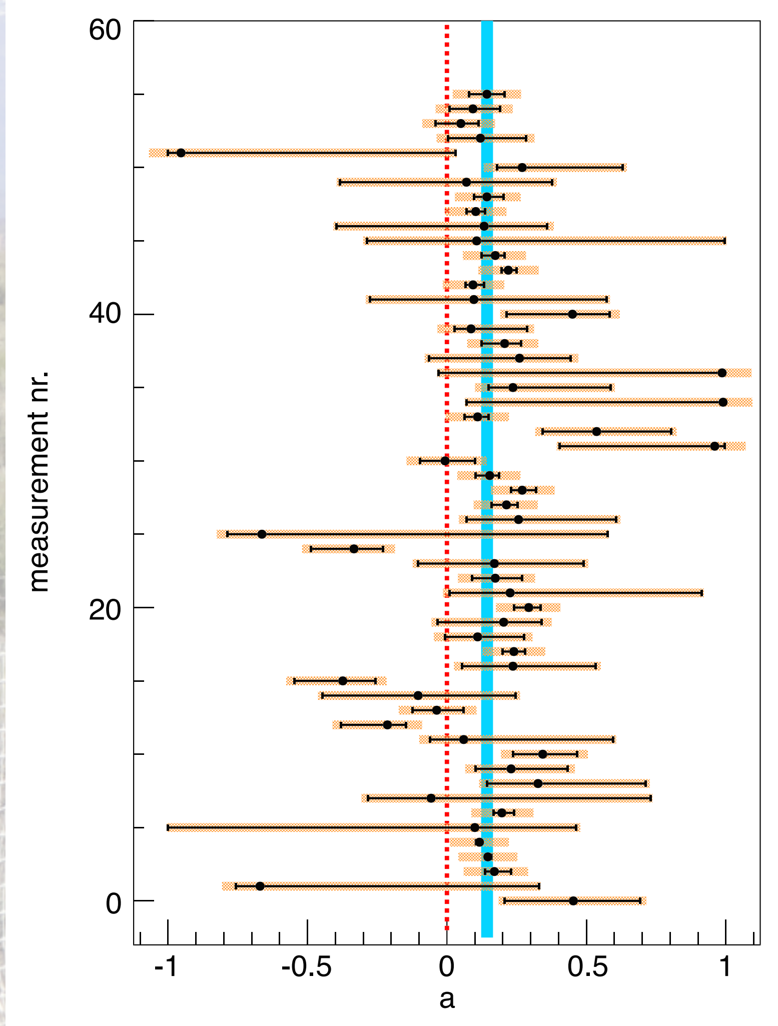


$$|E^G| \propto |\sin\alpha|$$

Angle between geomagnetic field and shower axis

$$a \equiv \sin\alpha \frac{|E^C|}{|E^G|}$$





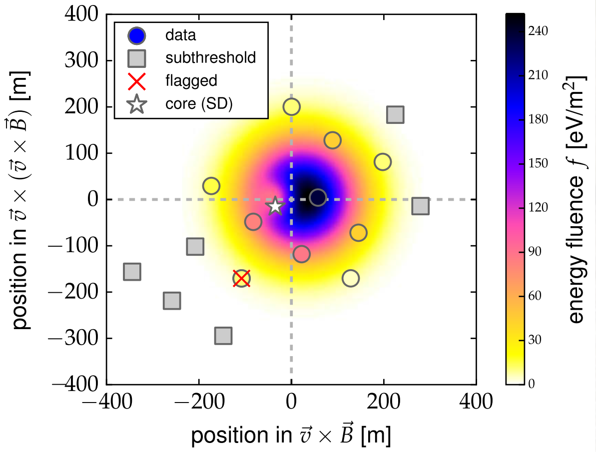
$\overline{a}$=0.14±0.02

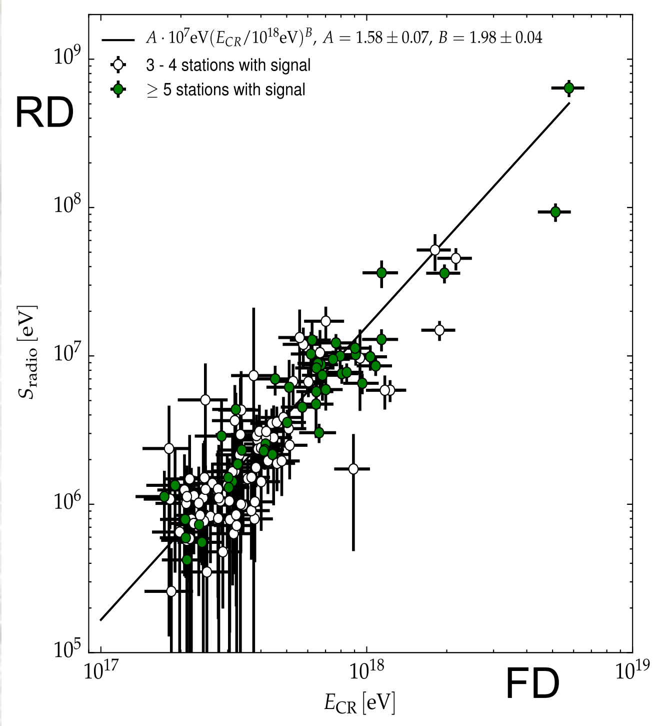
PRD 89 (2014) 052002

Radio detection of air showers: Energy measurement

$$\varepsilon(\vec{r}) = A\left[e^{-\left(\vec{r}+C_1\vec{e}_{\vec{v}\times\vec{B}}-\vec{r}_{\rm core}\right)^2/\sigma^2} - C_0\, e^{-\left(\vec{r}+C_2\vec{e}_{\vec{v}\times\vec{B}}-\vec{r}_{\rm core}\right)^2/\left(C_3\, e^{C_4\sigma}\right)^2}\right] \ \mathrm{eV/m^2}$$

$C_0 \ldots C_4$ zenith angle dependent determined from CoREAS MC; fit: A, $r_{\rm core}$, σ;



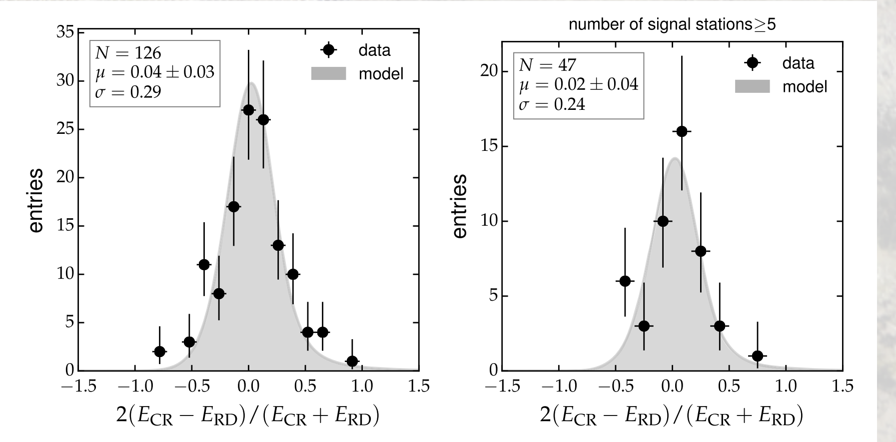


$$S_{\rm radio} = \frac{1}{\sin^2\alpha}\int \varepsilon(\vec{r})\,d\vec{r} = \frac{A\pi}{\sin^2\alpha}\left[\sigma^2 - C_0 C_3^2\, e^{2C_4\sigma}\right] \ \mathrm{eV}$$

Energy in 30-80MHz radio

$$E_{30\text{-}80\mathrm{MHz}} = (15.8 \pm 0.7 \pm 6.7)\ \mathrm{MeV}\left(\sin\alpha\,\frac{E_{\rm Cosmic\ Ray}}{10^{18}\ \mathrm{eV}}\,\frac{B_{\rm Earth}}{0.24\ \mathrm{G}}\right)^2$$

Resolution:



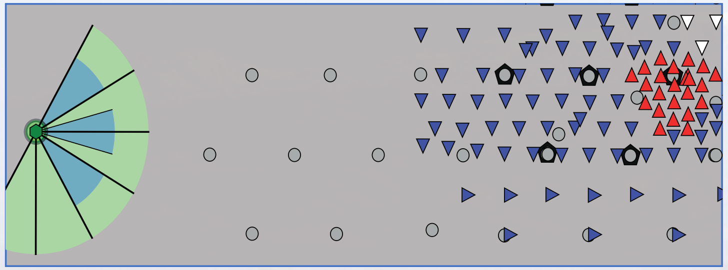
σ/E= 29%. 24% (FD≈20%)

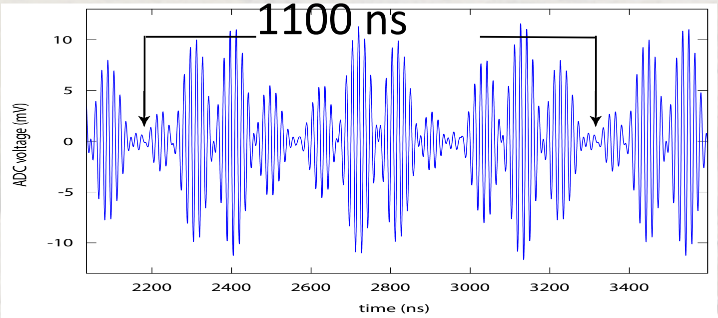
Compare to Fluorescence det:

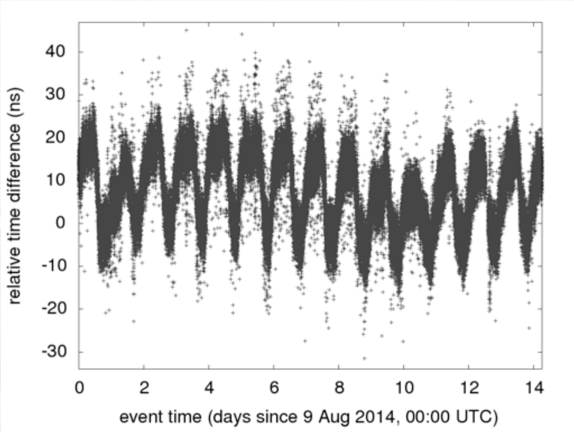
PRL 116 (2016) 241101
PRD 93, (2016) 122005

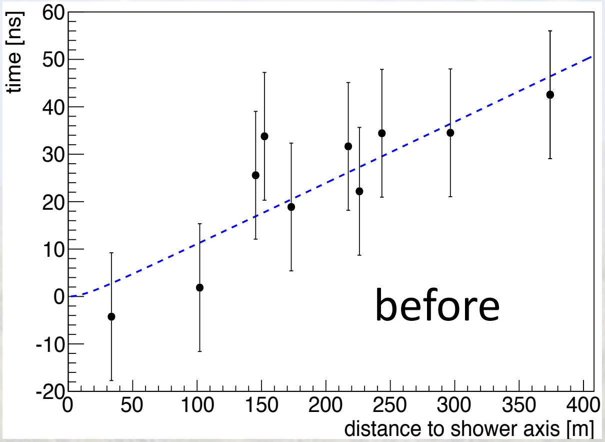
Radio detection of air showers: Direction measurement

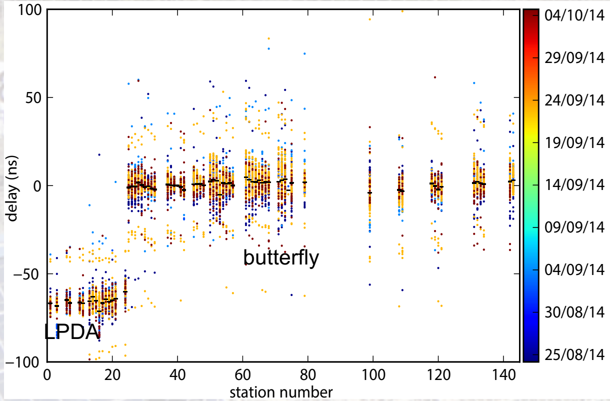
- GPS
- Beacon

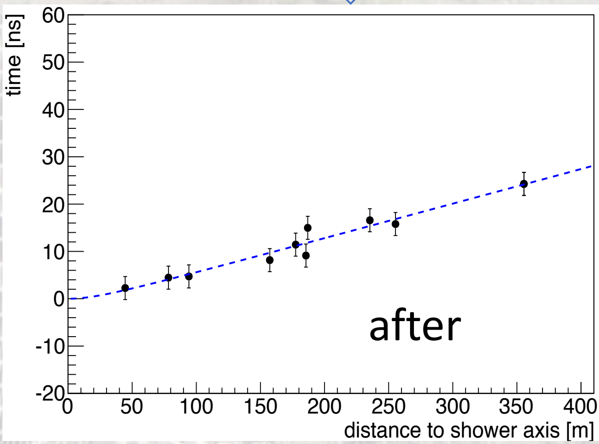




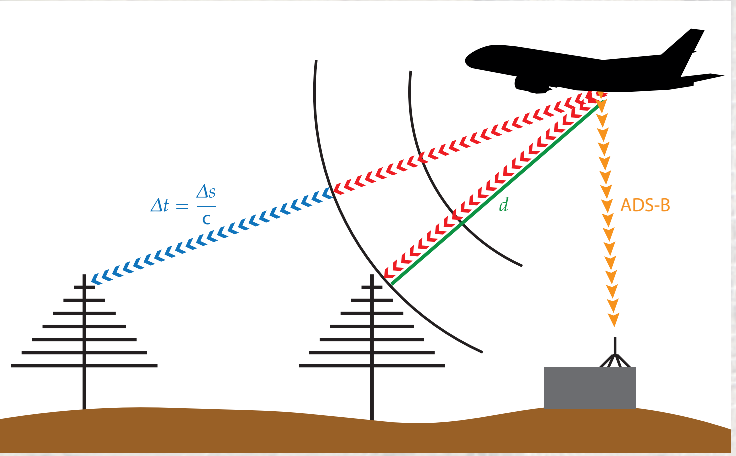


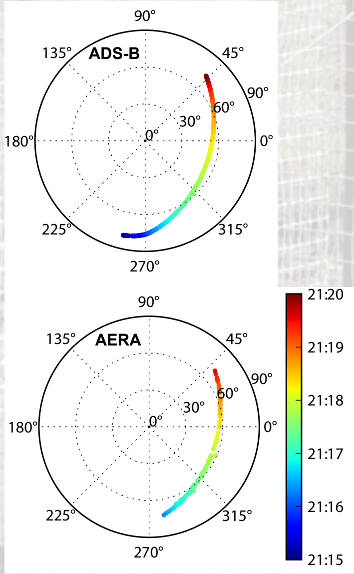






- Verify: Airplane





JINST 11 (2016) P01018

1 ns timing => angular resolution ~ 0.1°

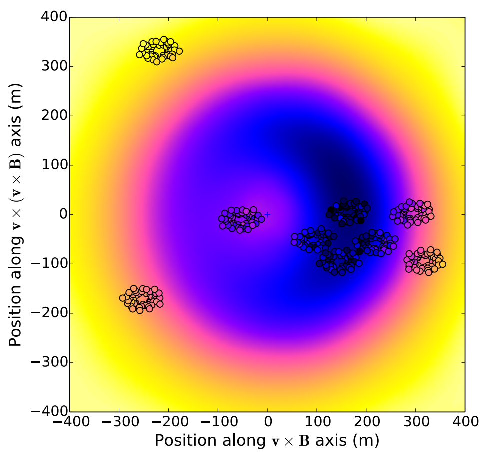
(airplane tracked much better than 1°)

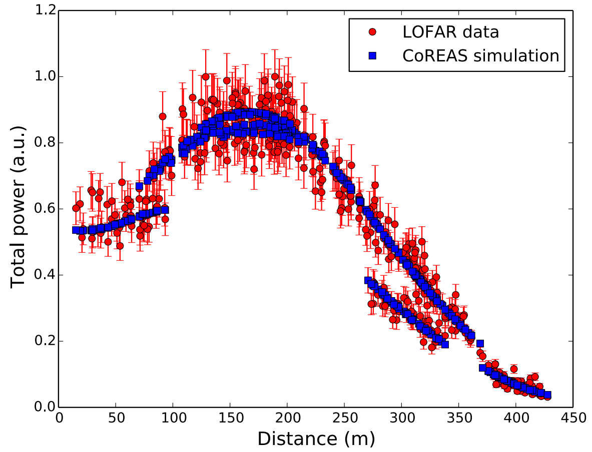
Radio detection of air showers: Composition measurement

- Simulated LDF method:

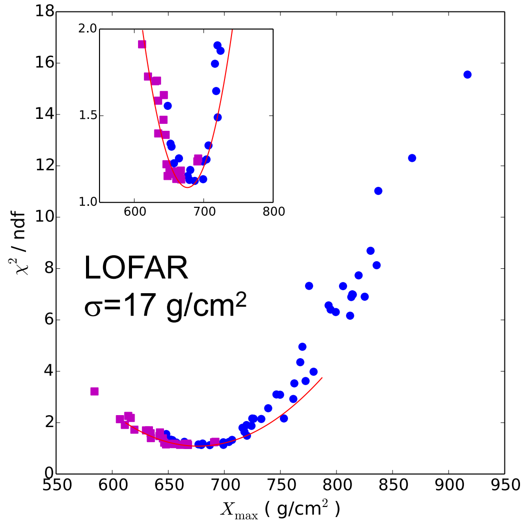
CoREAS to simulate same shower

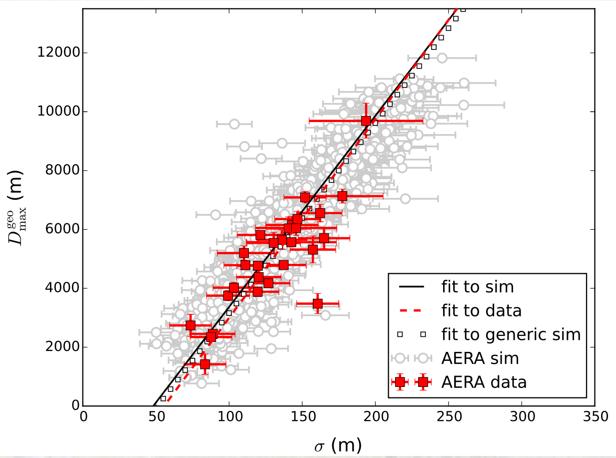
LDF fit parameter s most sensitive to X_{max}

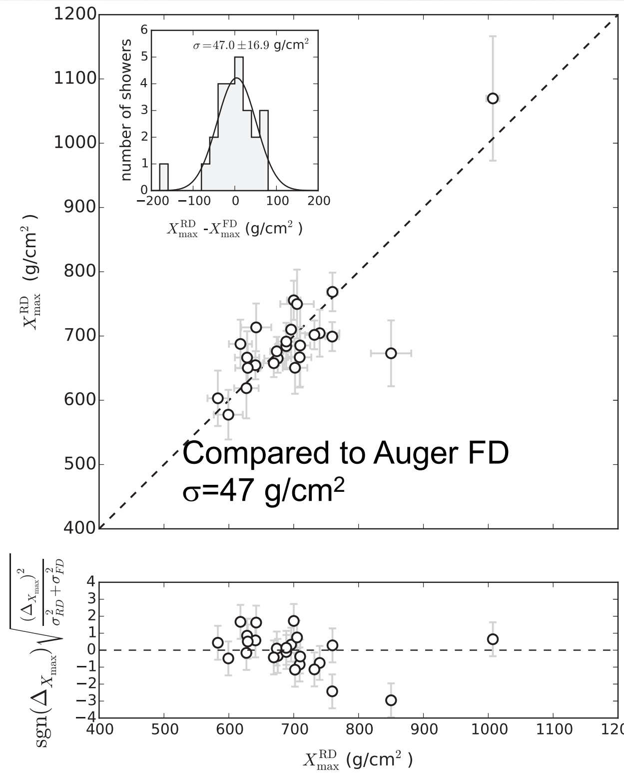




LOFAR: PRD 90 (2014) 082003

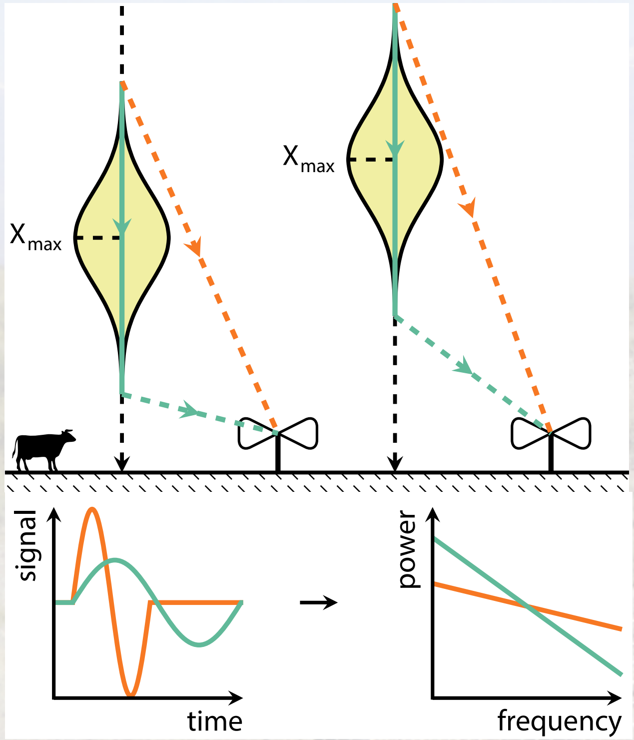


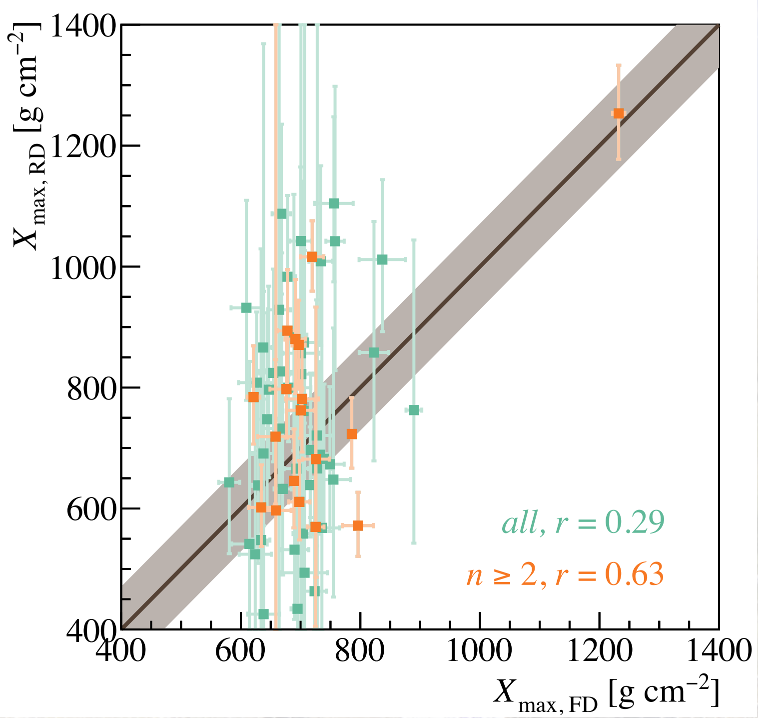


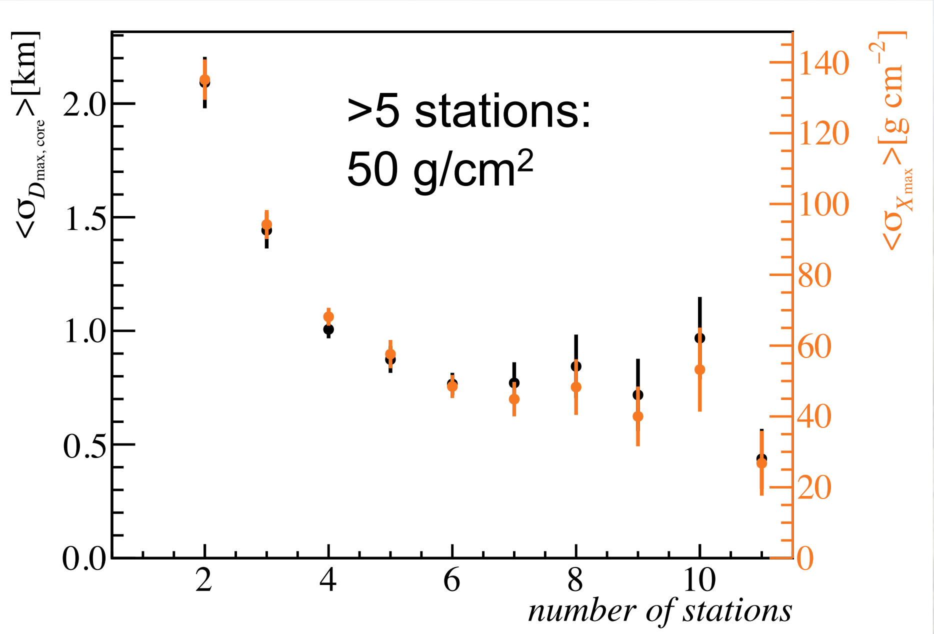


AERA:
PhD thesis Johannes Schulz, 2015,
Radboud University Nijmegen

Radio detection of air showers: Composition measurement





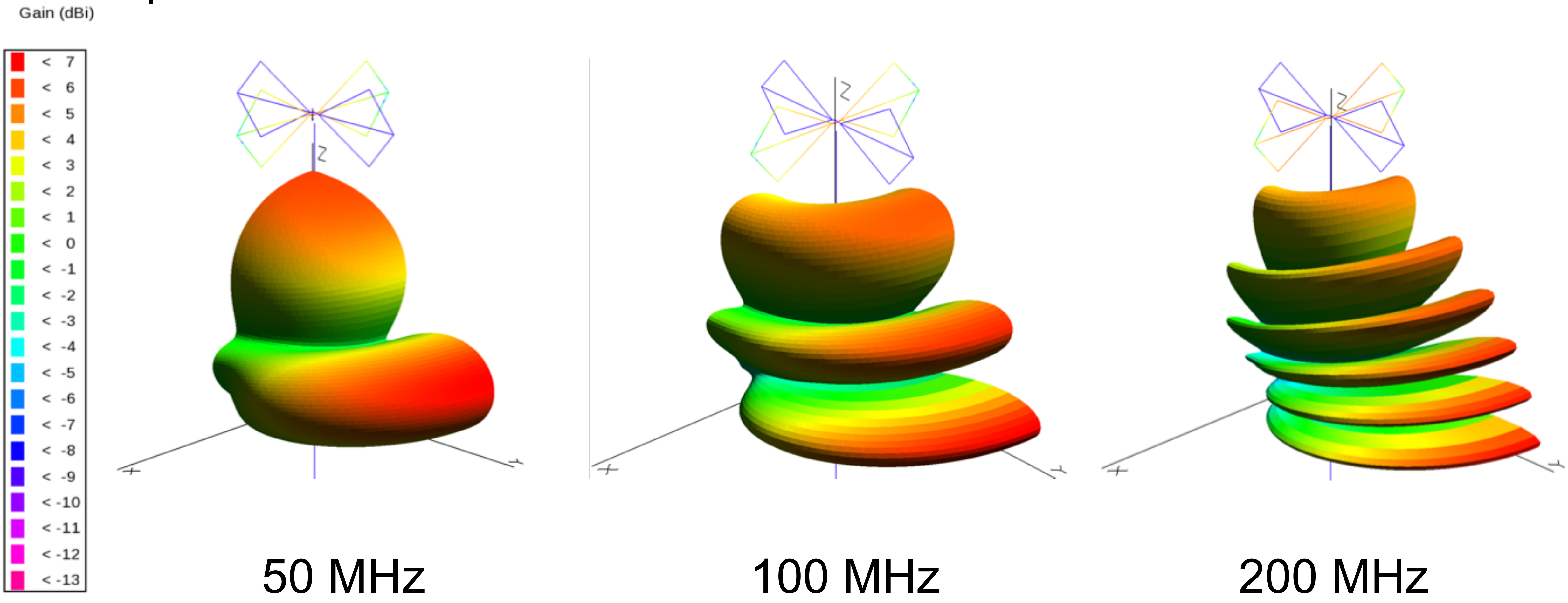


- Spectral index
  - Pulse projection in time domain
  - Spectral slope in frequency domain
  - Direct geometrical estimator, quasi-independent of MC
- Radius of curvature
  - Work in progress, new timing calibration should improve a lot

PhD thesis Stefan Jansen, 2016,
Radboud University Nijmegen

Radio detection of air showers

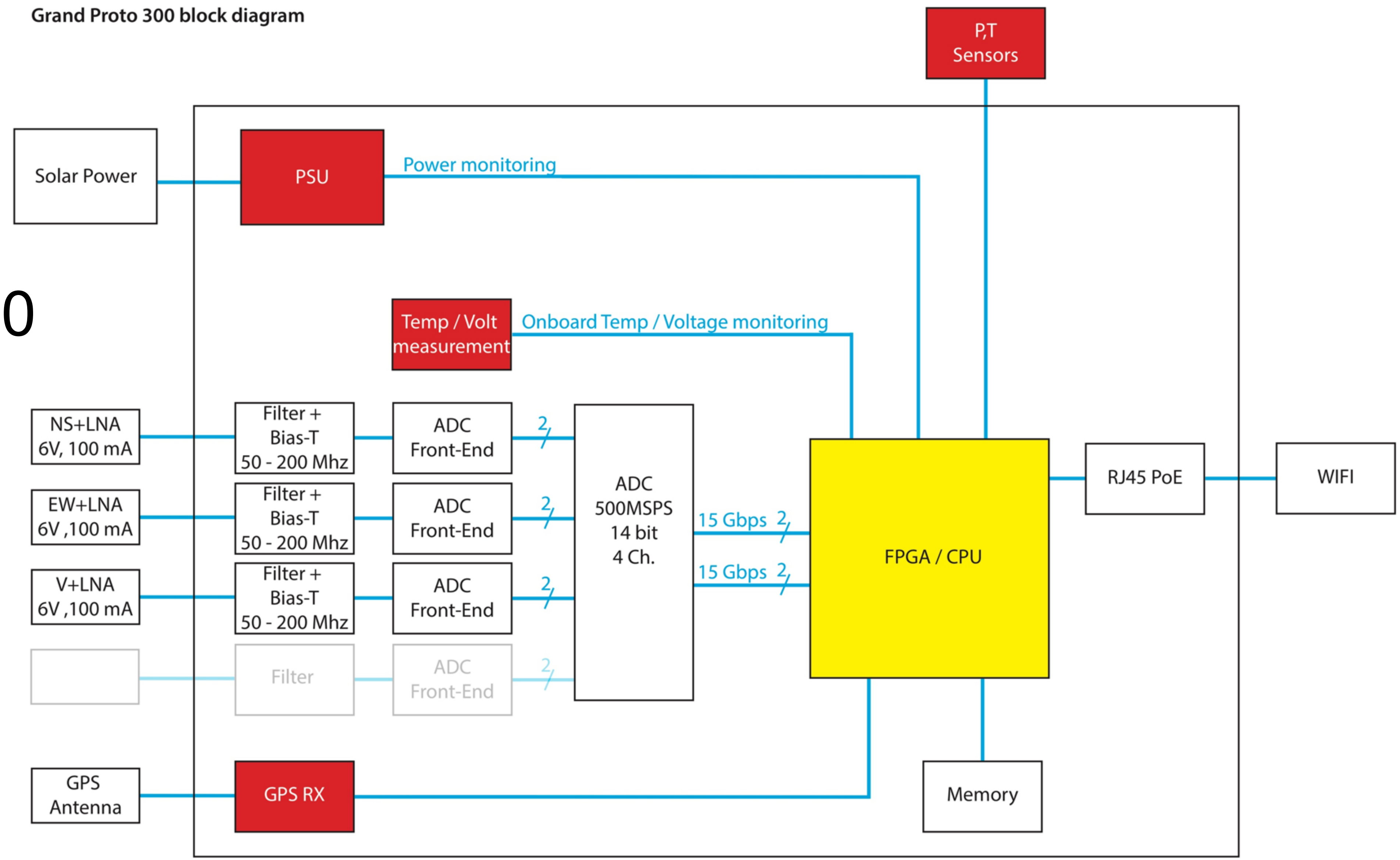
- Practical issues:
  - Optimise for horizontal showers



Radio Detector Station

functional design for GrandProto300

(3 antenna polarisations)



Radio detection of air showers

- Practical issues:
  - Optimise target/detector placement:

Tau shower simulation

E = 3x10[8] GeV

50 m above ground, 0.5[o] elevation

Area above thresholds:

Conservative: 100 μV/m

$$\Omega^a(E_{\rm sh}) = 0.47 \log\left(\frac{E_{\rm sh}}{10^{17}\ {\rm eV}}\right) + 0.9^\circ$$

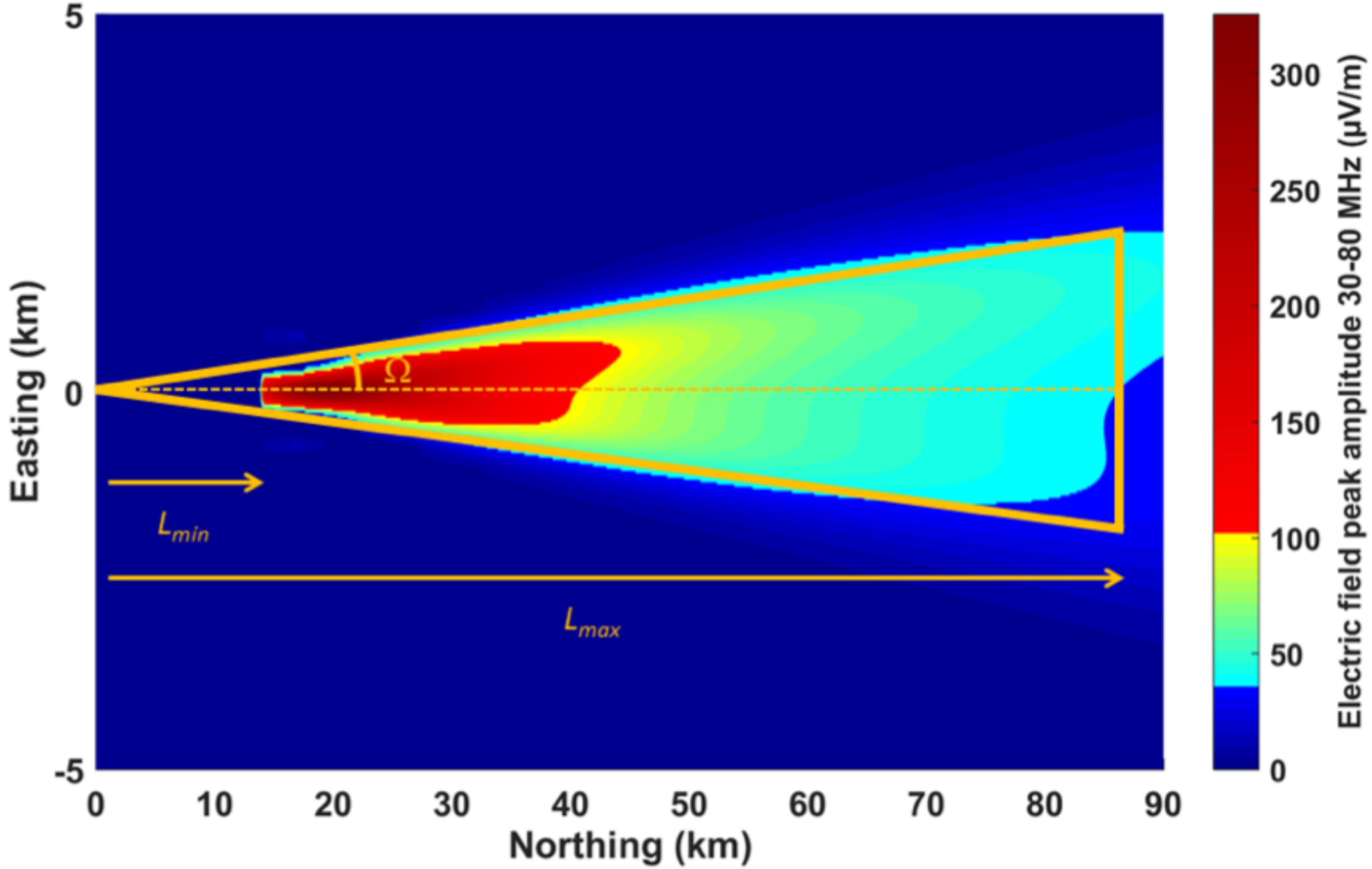
$$L^a_{\rm max}(E_{\rm sh}) = 39 \log\left(\frac{E_{\rm sh}}{10^{17}\ {\rm eV}}\right) + 55\ {\rm km}$$

Aggressive: 30 μV/m

$$\Omega^c(E_{\rm sh}) = 0.42 \log\left(\frac{E_{\rm sh}}{10^{17}\ {\rm eV}}\right) + 0.45^\circ$$

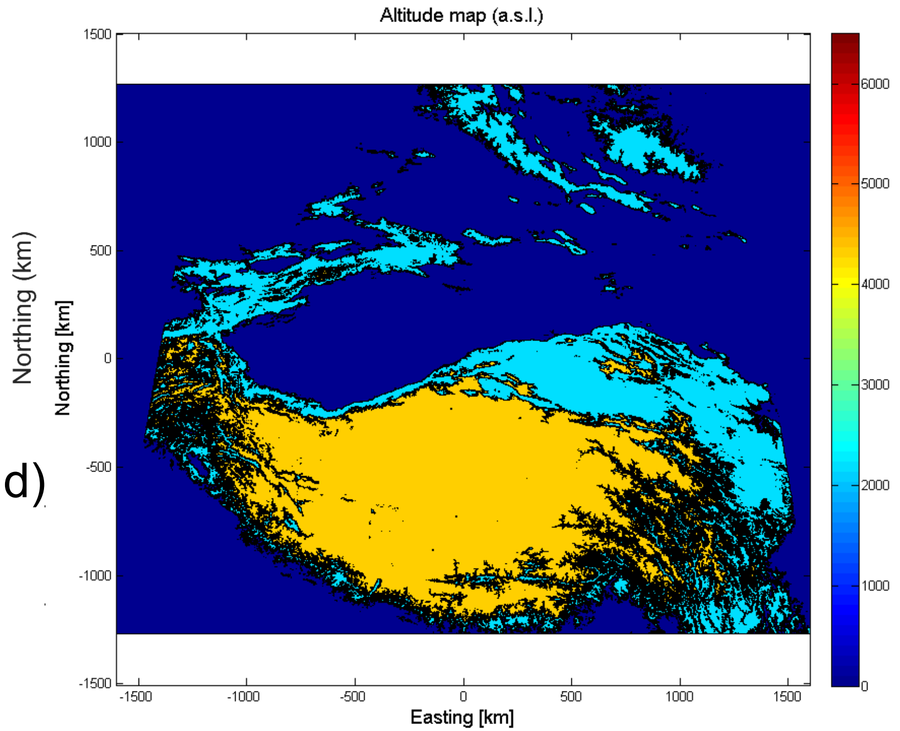
$$L^c_{\rm max}(E_{\rm sh}) = 27 \log\left(\frac{E_{\rm sh}}{10^{17}\ {\rm eV}}\right) + 22\ {\rm km}$$

$$L^a_{\rm min} = L^c_{\rm min} \approx 14\ {\rm km}$$

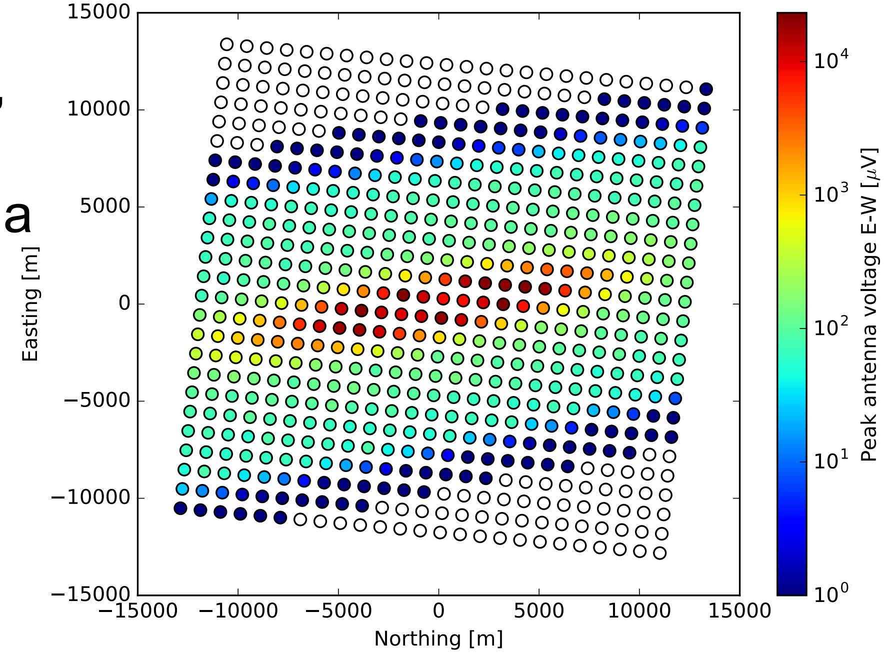


Radio detection of air showers

- Practical issues:
  - Optimise target placement: mountains !
    (e.g. Tian Shan in North-West China)
    - Split array in Hot Spots (any mountains in the world)
  - Optimise detector grid size



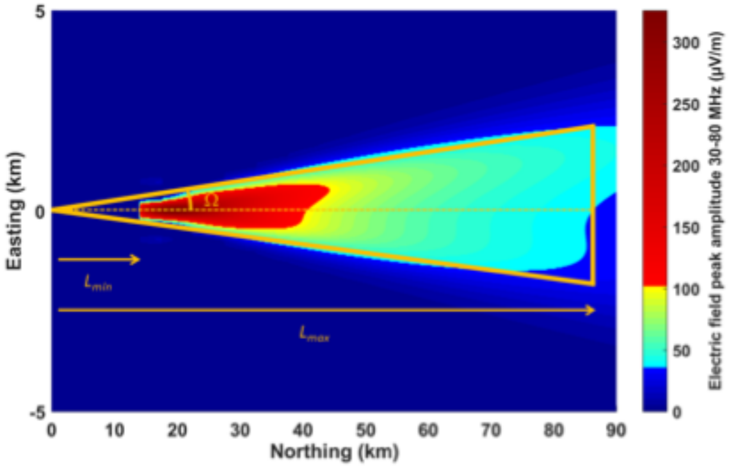
Simulation:
E=10^{10} GeV,
θ=80º,
1 km antenna
Spacing



Work in progress…

Valentin Niess & Anne Zilles

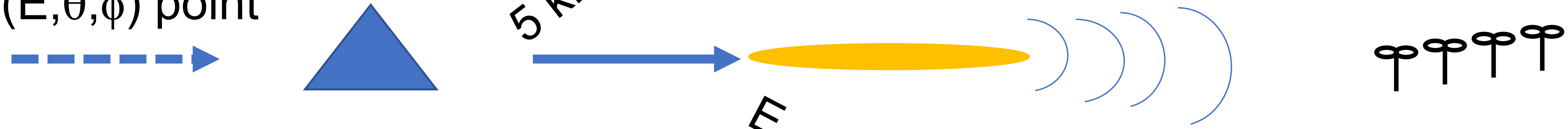
ν_τ Event Simulation



50-200 MHz
simulation
in progress

$10^8 < E_\nu < 10^{11.5}$ GeV
$86^o < \theta_\nu < 93^o$
$0^o < \phi_\nu < 360^o$
Until 100 events
in fiducial for each
(E,θ,ϕ) point

τ decay length =
5 km * (E/10^8 GeV)

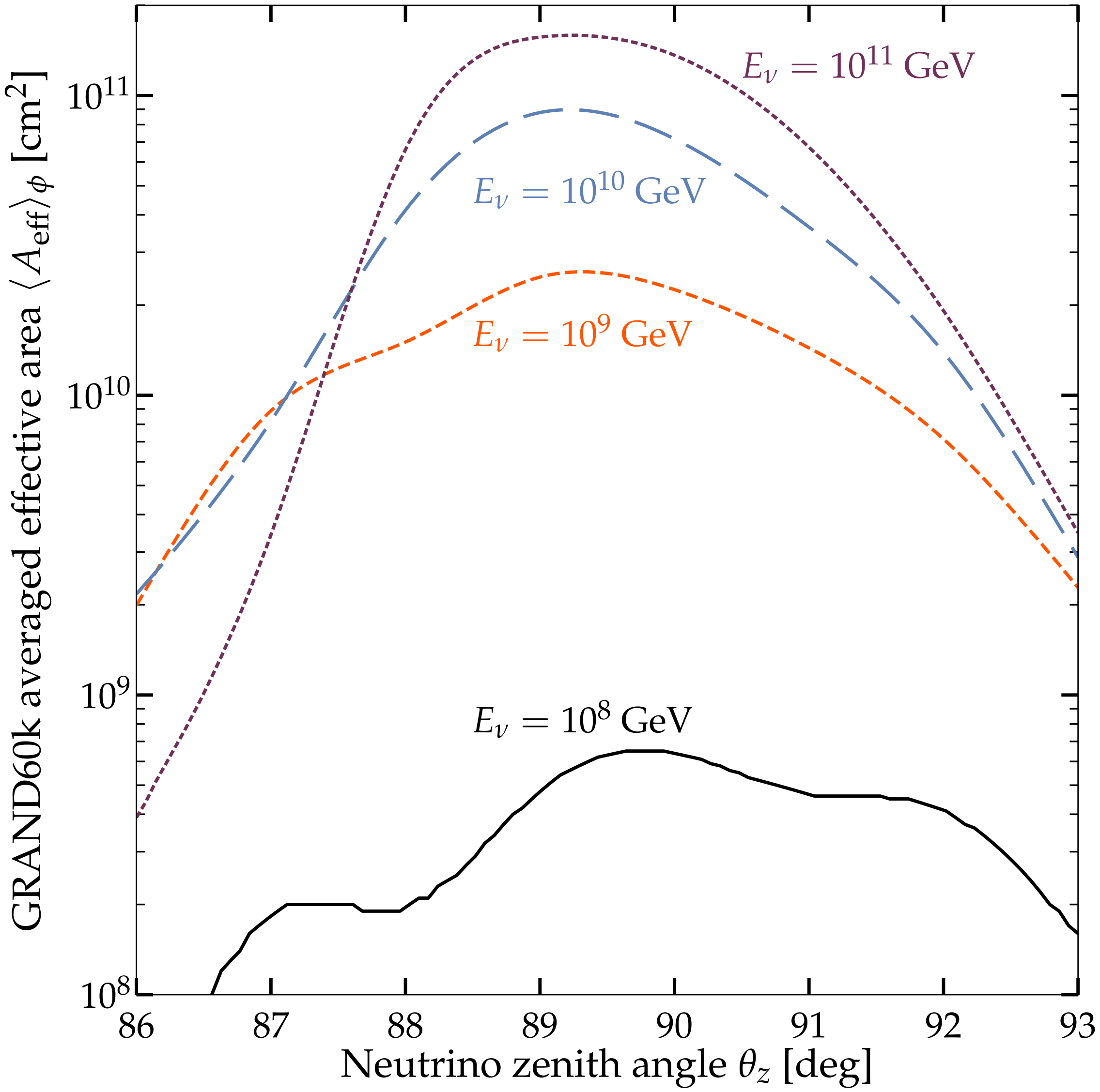


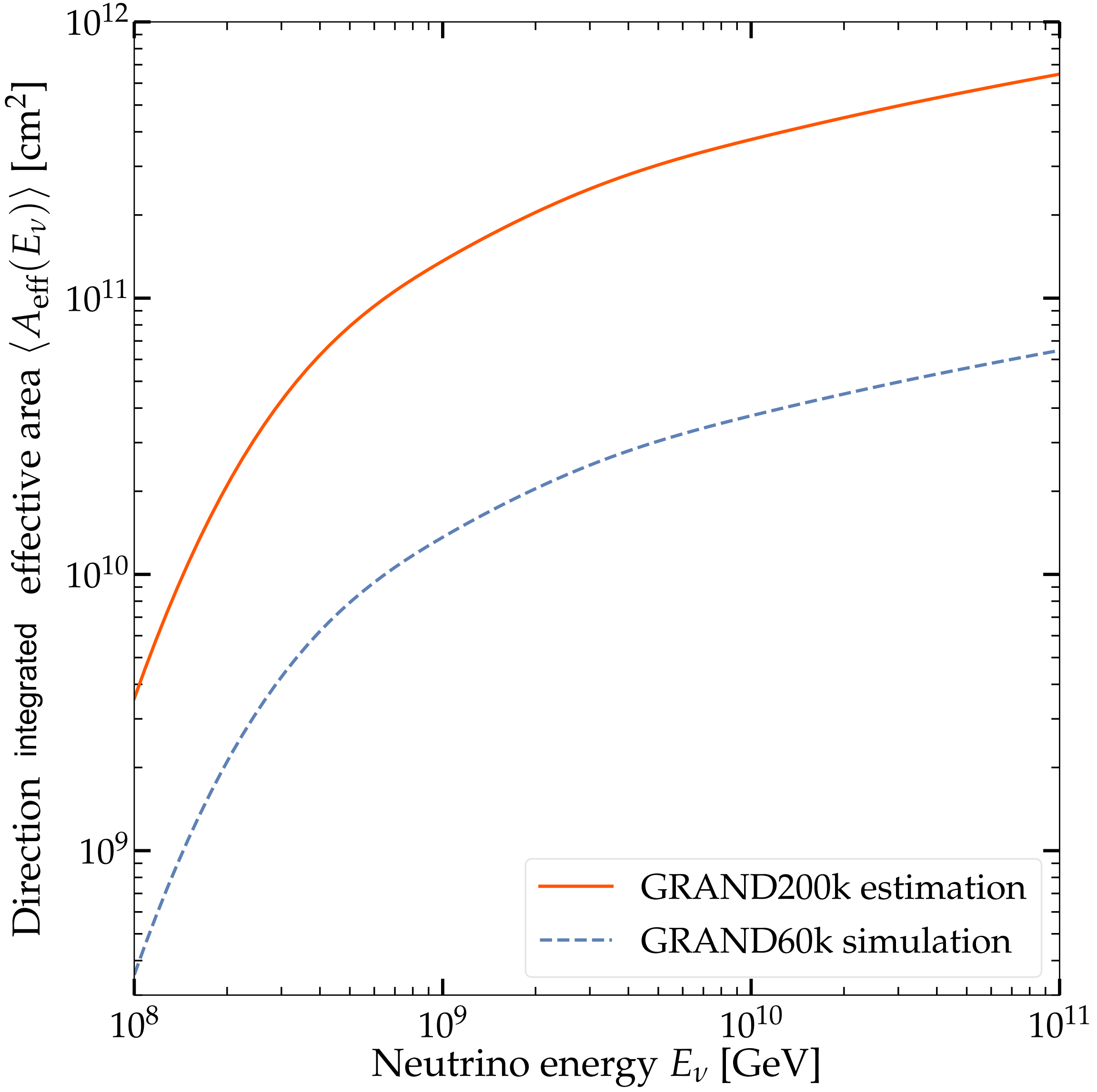
$E_{shower} > 10^7$ GeV

Tian Shan area
(86º44'E, 42º57'N)
NASA satellite
topographic map

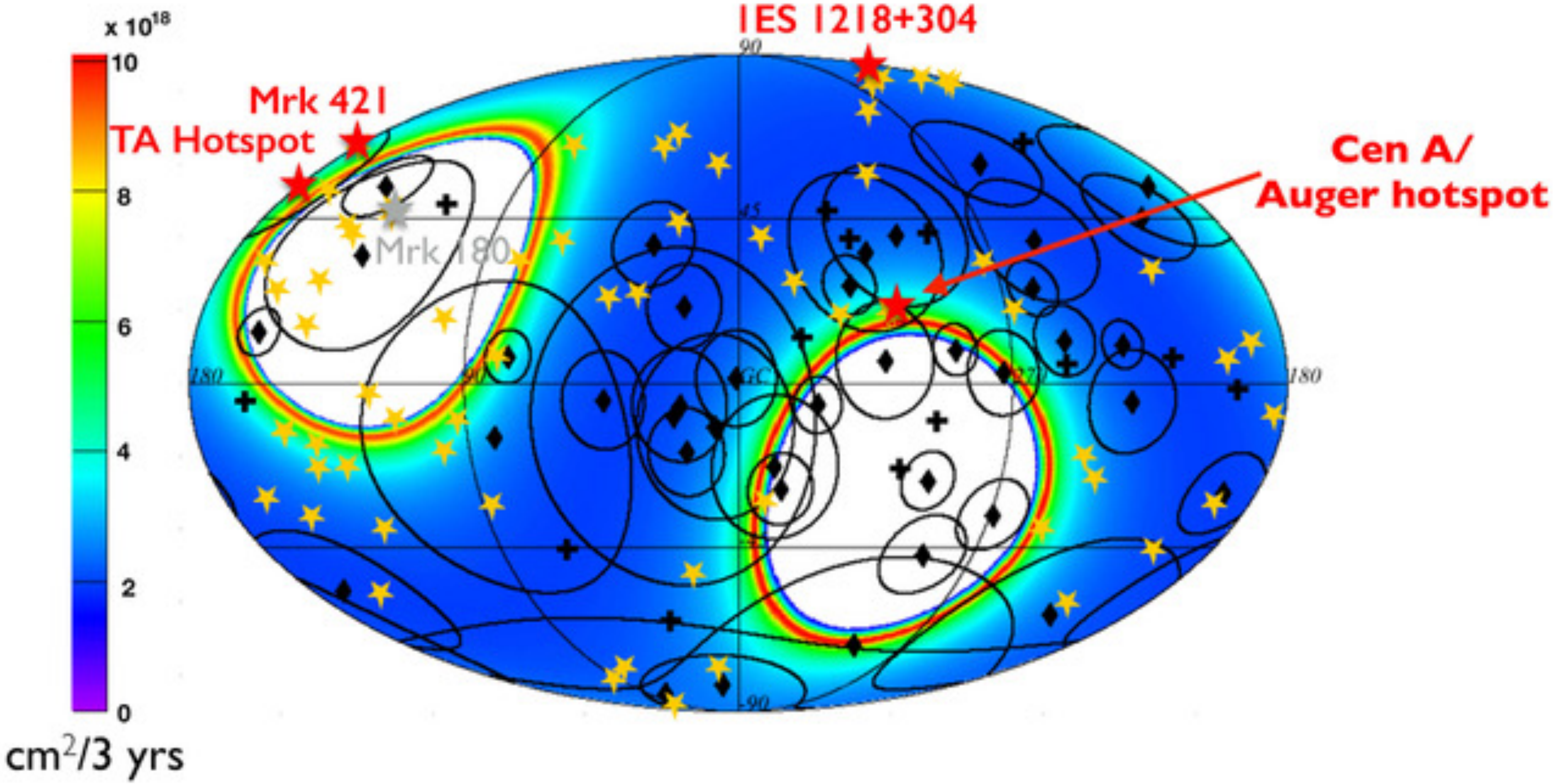
60 000 km^2 area
800 m station spacing
Detection = 8 neighbouring
stations above threshold

ν_τ Simulation: Effective area





ν_τ Simulation: Exposure (for $E_\nu = 10^9$ GeV)

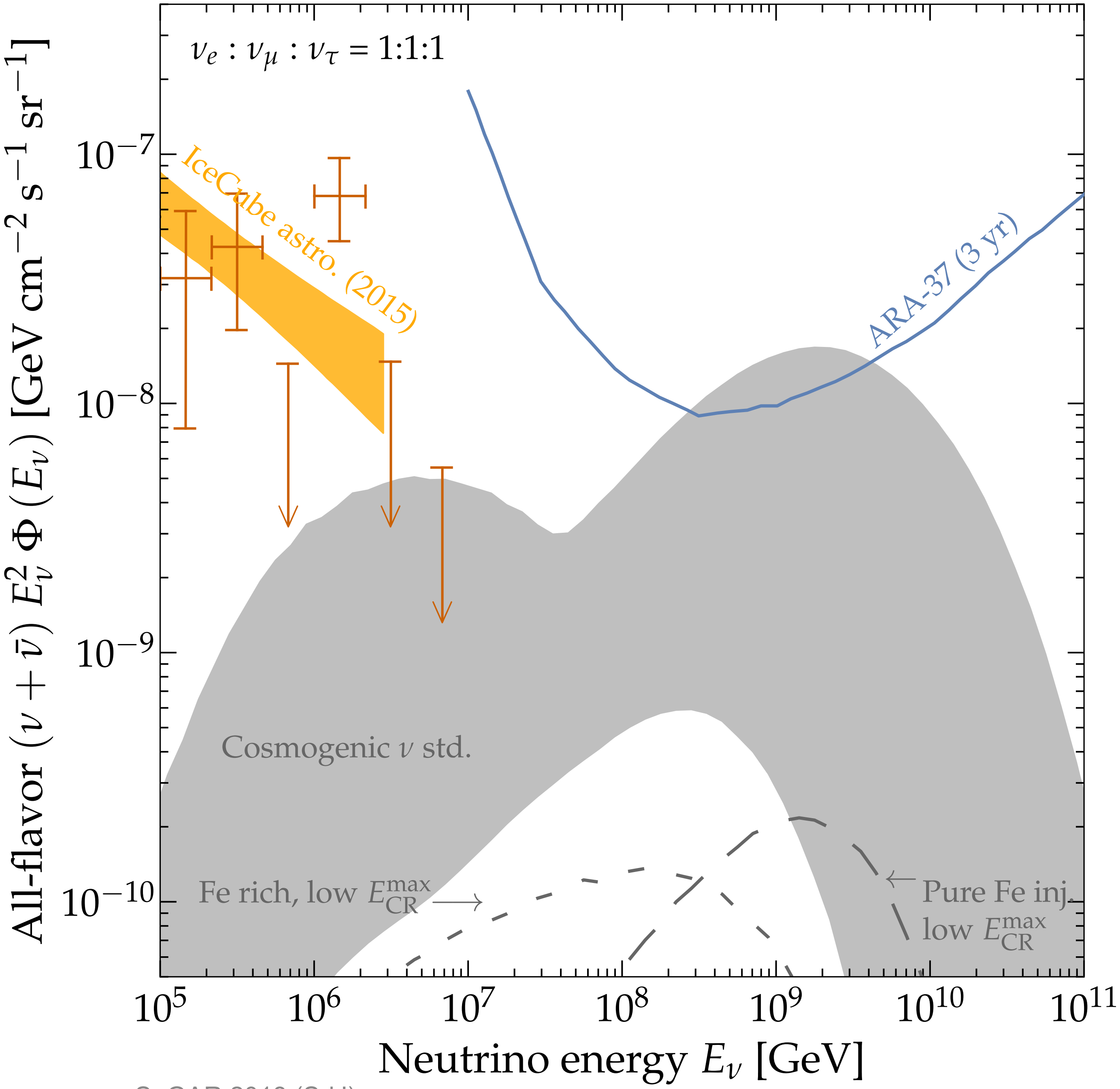


ν_τ Simulation: Science Reach

- First (?) $E_\nu > 10^8$ GeV
- Point Sources, multi-messenger APP
- Cosmogenic Origin, distinguish scenarios

Neutrinos with:

- Highest energies
- Longest baseline



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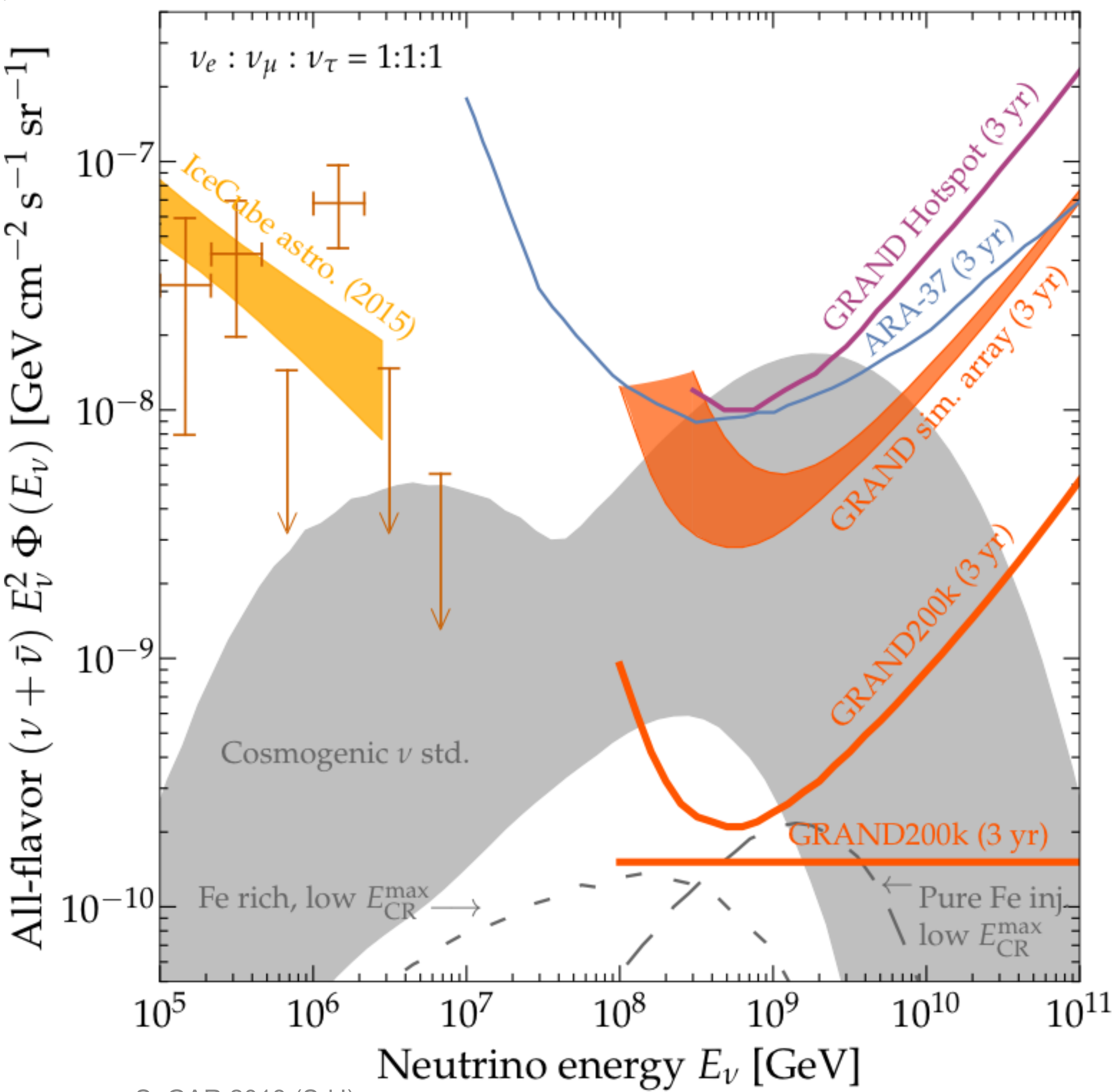

Giant Radio Array for Neutrino Detection

- But GRAND

  is much more:

Giant Radio Array for Neutrino Detection

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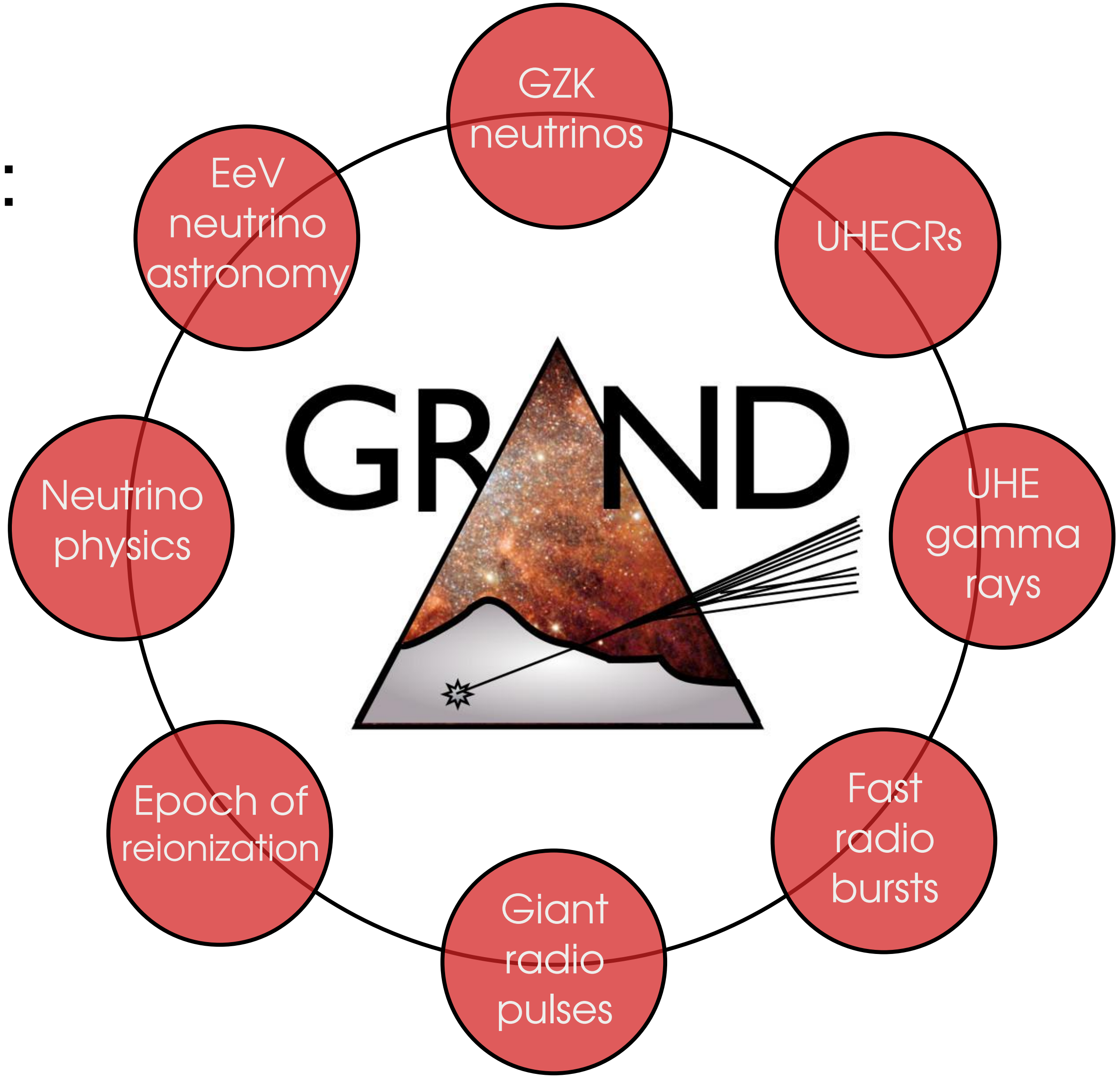


ν_τ physics reach

- General new physics effects typically scale as: $\kappa_n * E^n * L$

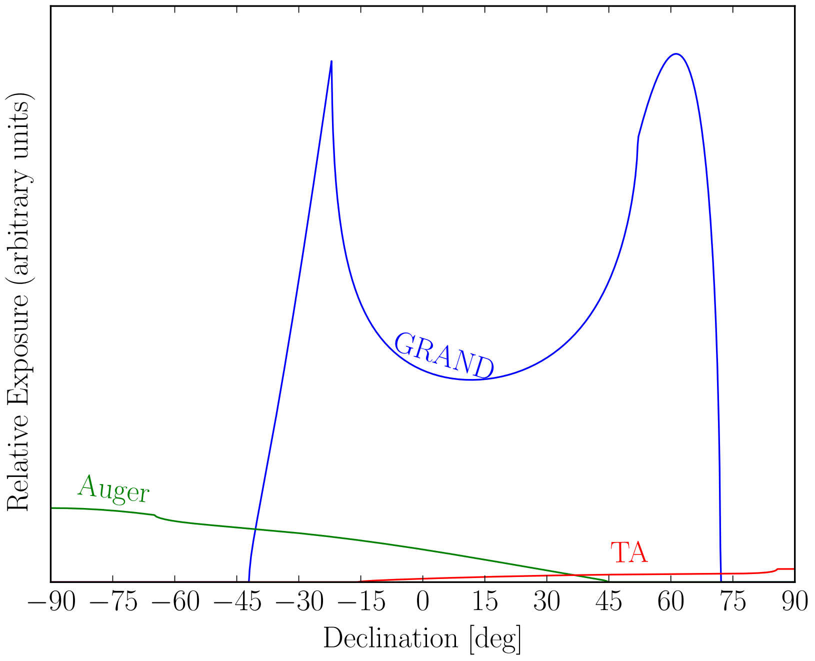
  GRAND sensitivity: $\kappa_n \sim 4*10^{-50}\,(E/EeV)^{-n}\,(L/Gpc)^{-1}$ [EeV^{1-n}]

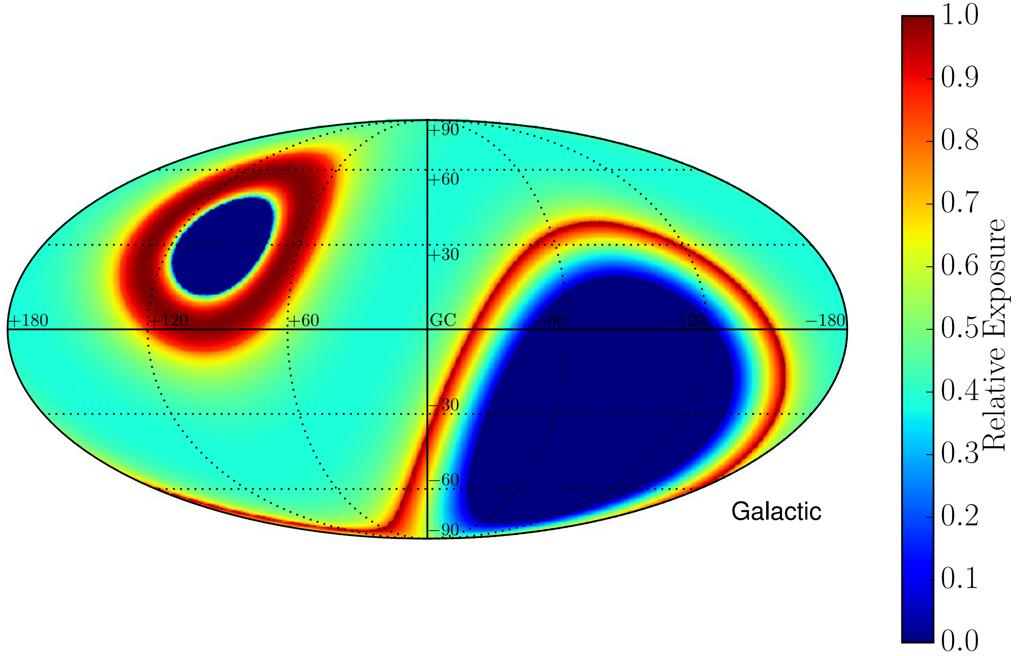
  Current limits: $\kappa_0 < 10^{-32}$ EeV and $\kappa_1 < 10^{-33}$

- UHE Neutrino cross section
  - Survival rate as a function of traversed material (angular distribution)
- New physics through energy spectrum
  - Resonances or other deviations from smooth spectrum
- Flavour composition
  - Requires other experiments to measure ν_e, ν_μ or all flavours. (e.g. ARA, ARIANNA, ANITA, CHANT, POEMMA,…)
  - GRAND sensitivity to ν_e needs more study

Ultra-High-Energy Cosmic Rays

- Exposure:
- Assuming fully efficient for:
  - 65º<θ<85º
  - E>10^{10} GeV



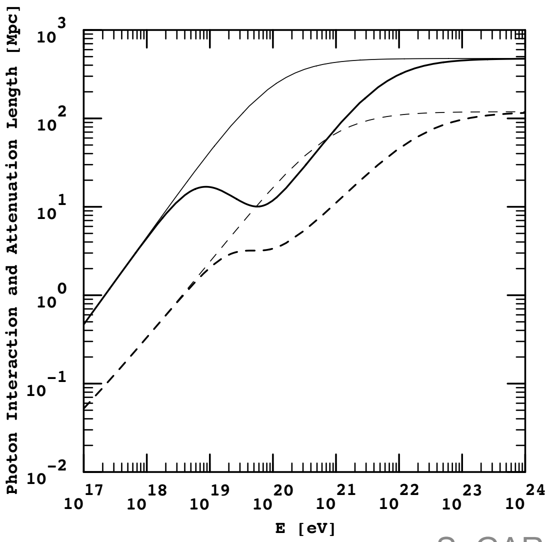


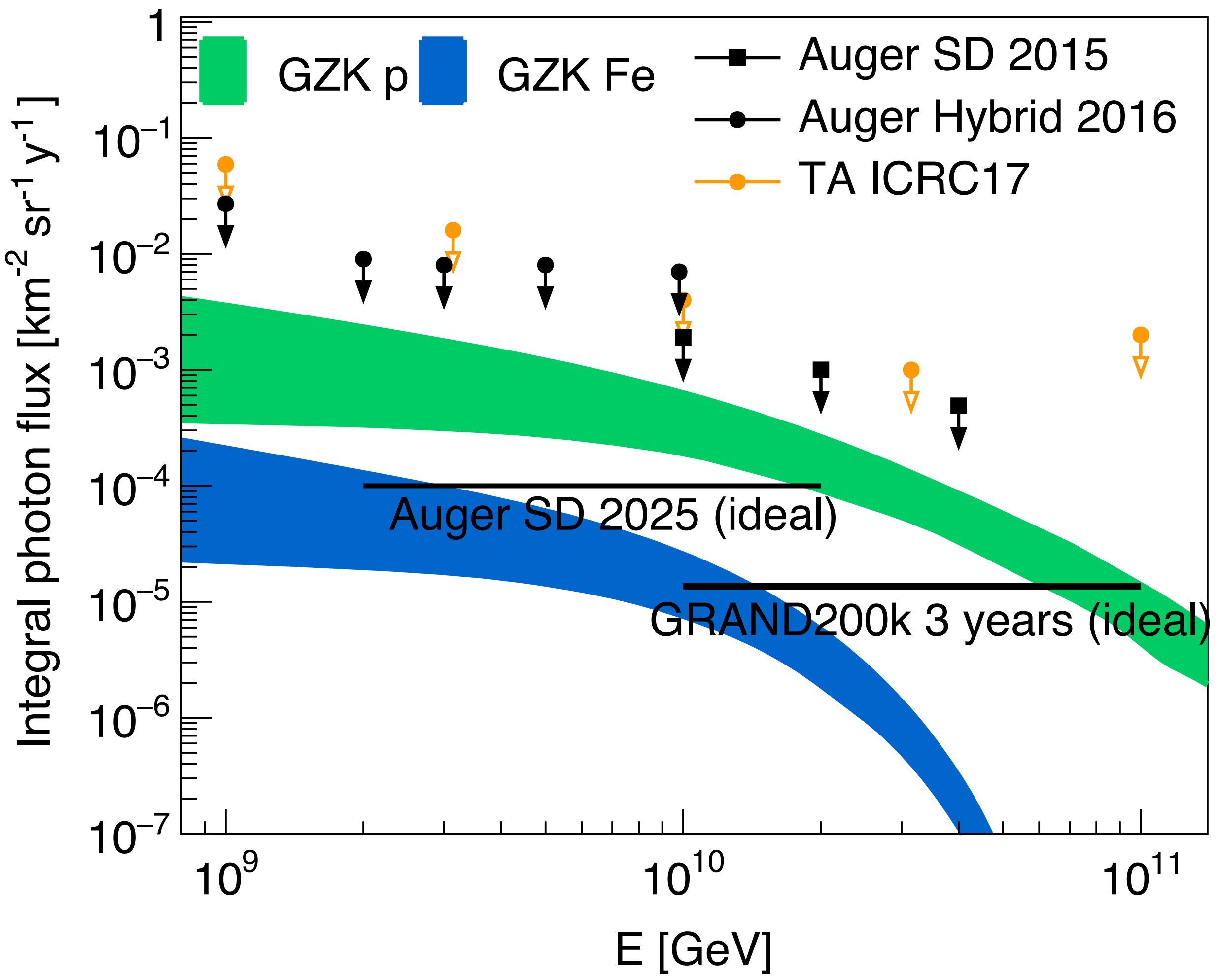
- 32000 events with E>$10^{10.5}$ GeV in 5 years
  - Proton astronomy even at small proton fraction
  - Proton-air & nucleus-air cross section at highest energy

Requires excellent event-by-event composition measurement !

Ultra-High-Energy Gamma Rays

- Include:
  - Landau-Pomeranchuk-Migdal effect
- Not included:
  - Pre-showering in magnetic field
- Separation based on X_{max} gives negligible hadron background
- Photon range typically 10's to 100 Mpc depending on interactions with unknown radio background
- Cosmogenic origin
- ALP sensitivity

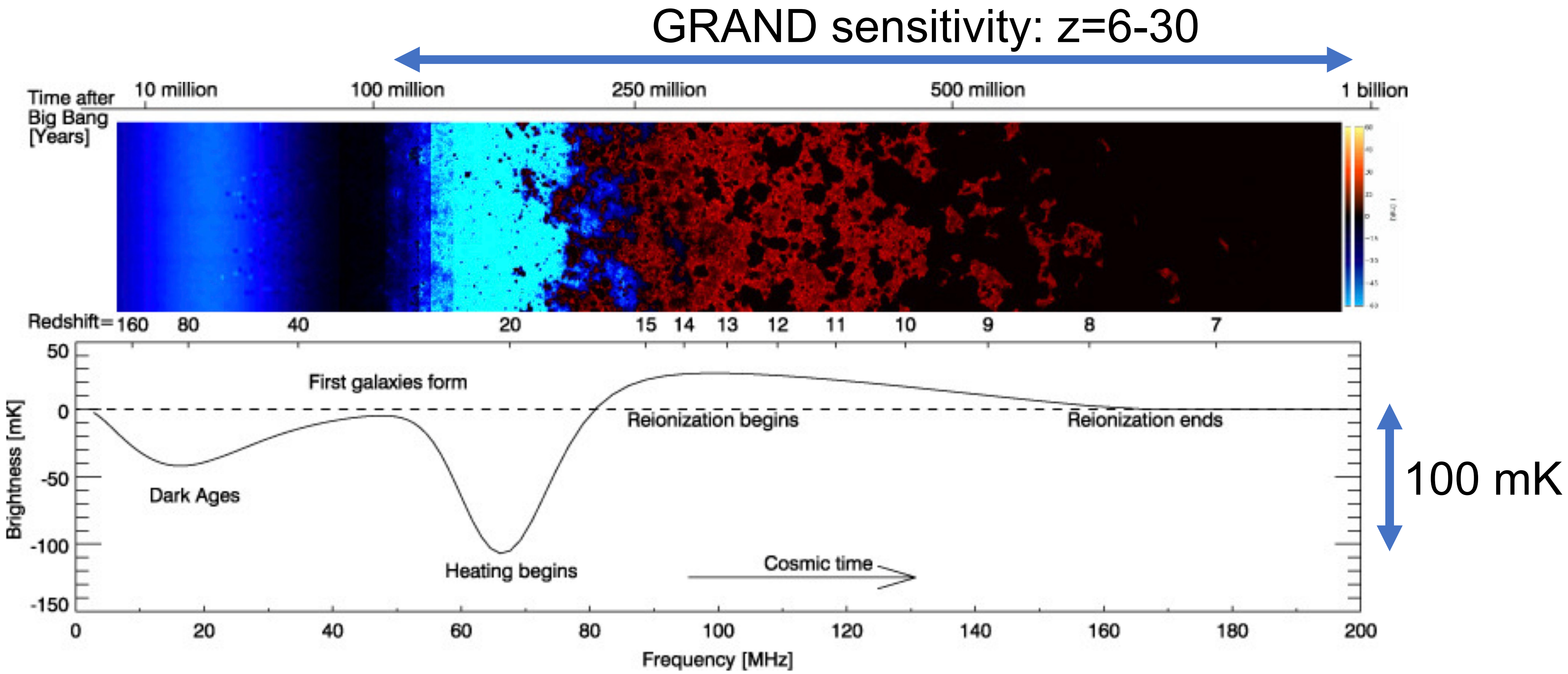




GRAND challenge:
Get photon sensitivity at lower E

Cosmology: Epoch of reionisation

- GRAND sensitive to 21 cm radio background

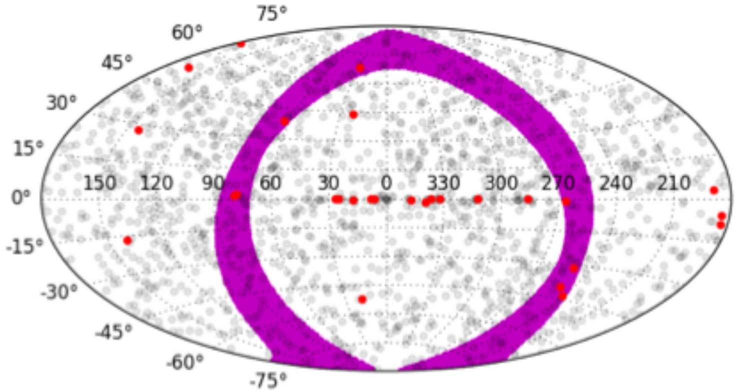


- Detection challenge: signal resolution 10 mK, typical foreground 100 K

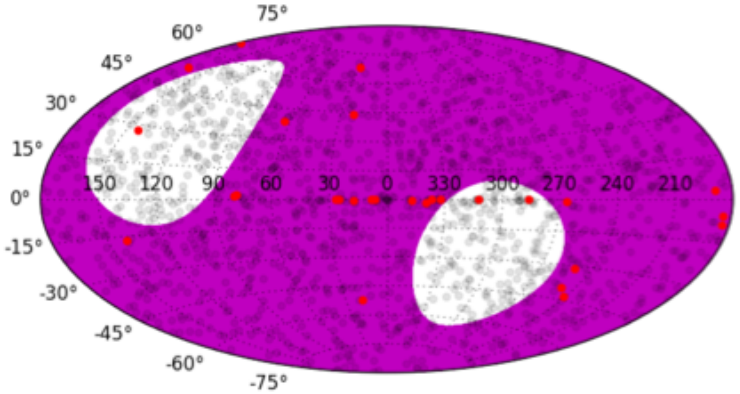
Fast radio bursts and Giant radio pulses

- FRB:
  - So far ~20 Fast Radio Burst detected (expect few 1000/day)
  - So far only 1 repeater
  - Also emission in 50-200 MHz ?
- GP:
  - ~1000 shorter and brighter than FRBs
  - Related to (some) pulsars
  - Also observed in 50-200 MHz range (less well studied so far)
- Exposure

1 hour



24 hours

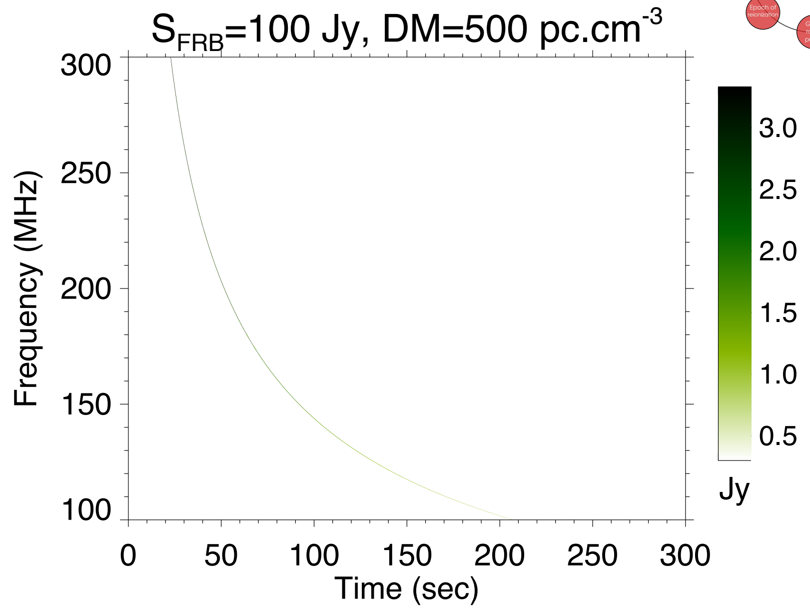


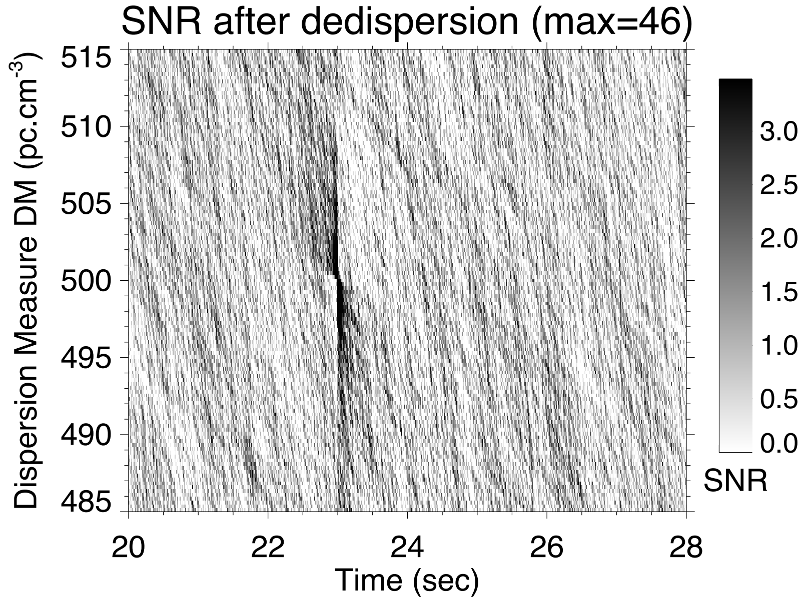
- Trade-off of number and distribution of hot spots

Fast radio bursts and giant radio pulses

- Sensitivity study
  - FRB simulation with varying spectrum (α=0-1) and luminosity (10-1000 Jy)
  - Dispersion Measure DM=500-1000
  - Apply de-dispersion analysis
  - Integrate in time: no direction resolution
- Expect to see 100-460 FRBs

  (cf. up to today 20 observed)
- Similar analysis strategy for GPs
- Special needs to DAQ, using maximum bandwidth
- May already work with GRANDProto 300





Staging and Time line

	GRANDProto35 (2018)	GRANDProto300 (2020)	GRAND10k (2025)	GRAND200k (203X)
Goals	**Standalone** radio detection of EAS Very good **background rejection**	Standalone radio detection of **very inclined showers** (θ>65°) induced by high energy cosmic rays (>10^9 GeV)	First GRAND subarray, **sensitivity comparable to ARA/ARIANNA on similar time scale**, allowing potential 1st discovery of cosmogenic neutrinos	**First neutrino detection at 10^9 GeV even with pessimistic fluxes and/or neutrino astronomy**
Setup	35 radio antennas 21 scintillators 	• 300 Horizon Antennas over 300 km^2 • Fast DAQ • Solar pannels (day use) + WiFi data transfer • TBD: Array of surface muon detectors	DAQ with discrete elements, but mature design for trigger, data transfer, consumption	200'000 antennas over 200'000 km^2 Hotspots could be in different continents
Budget & stage	160k€, fully funded by NAOC+IHEP, deployment 2018 @ Ulastai	1.3 M€ to be deployed in 2019 Funded in China	1500€ / detection unit	**Industrial scale allows to cut costs down: 500€/unit** **➔ 120M€ in total**

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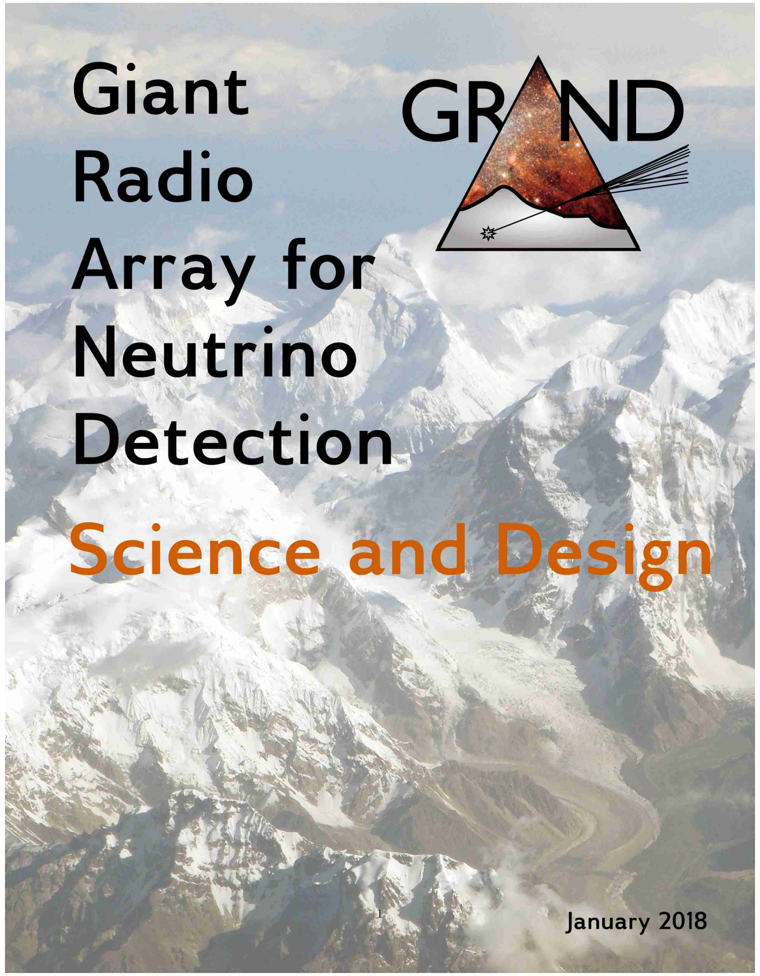

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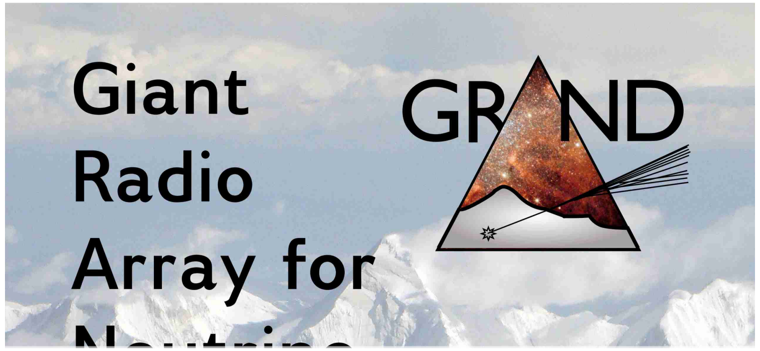

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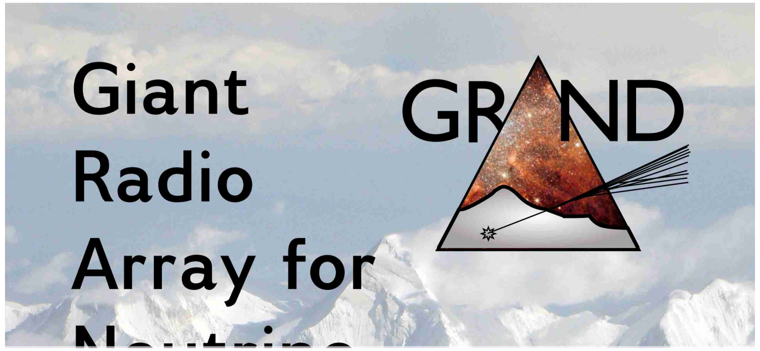

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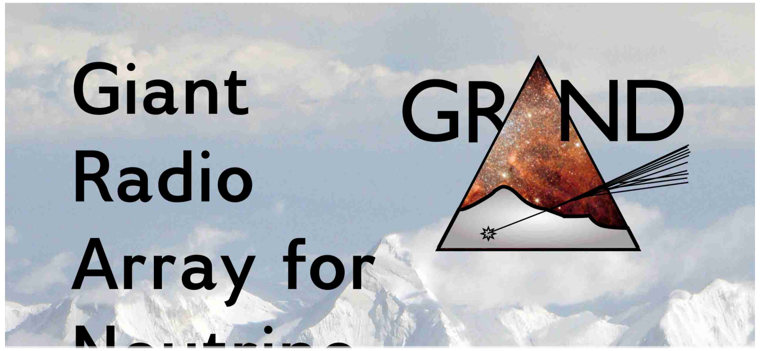
White paper and Proto-Collaboration

- White paper being written
- Will be published in few months



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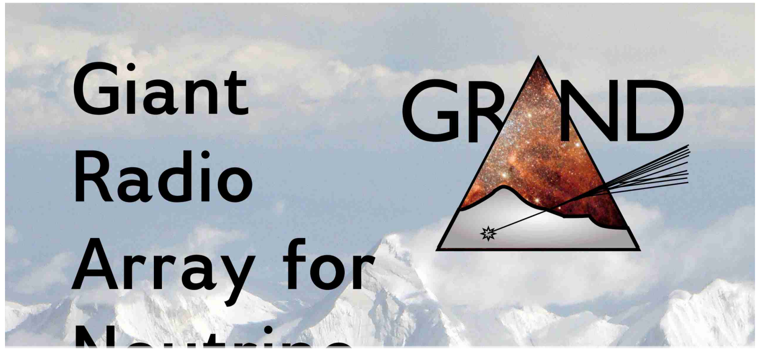

White Paper Editor

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Summary and Outlook

- Highest energy cosmic rays still a mystery in many respects
- UHE neutrinos and photons expected, but not yet observed
- Need orders of magnitude more exposure than Auger/TA

- GRAND:
  - Will observe UHE cosmogenic neutrinos and do neutrino astronomy and neutrino physics far beyond the current reach
  - Will observe a large number of UHECR and be able to do proton astronomy even at low proton fractions
  - Will do important cosmology and astronomy (FRB/GP)
  - Will be a very versatile multi-messenger observatory, capable of observing a large scale of new phenomena (if they exist)
  - Has already started, follows ambitious planning
  - Requires substantial funding and human resources