The Giant Radio Array for Neutrino Detection (GRAND)

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Outline

- Introduction;
  - Science case;
  - Detection principle;
  - Antenna design;
- Ultra High Energy messengers;
- GRANDProto300;
- Summary.

Introduction

- Ultra High Energy Cosmic Rays – UHECR:
  - Extraterrestrial charged particles with energies above 10^{18} eV = 1 EeV;
  - Origin: Extragalactic – although no source identified;
  - Arrival direction studies;
  - Direct search from arrival direction studies;

Direct Search Challenges	Indirect Search Features

• Mass composition;
• Galactic and extragalactic magnetic fields;
• Low statistics at higher energies;
• Few events above 40 EeV from sources beyond 100 Mpc due to GZK effect;
	• Look for EeV γ rays and ν made by UHECR;
	• No magnetic field deflection;
	• Though not detected cosmogenic γ rays and ν should exist;
	  ○ UHE gamma rays do not reach Earth from beyond 10 Mpc due to interaction with CMB;
	  ○ The universe is transparent to UHE cosmogenic neutrinos, but the expected flux is tiny.

A rich science case

Slide by Kumiko Kotera

UHE neutrinos

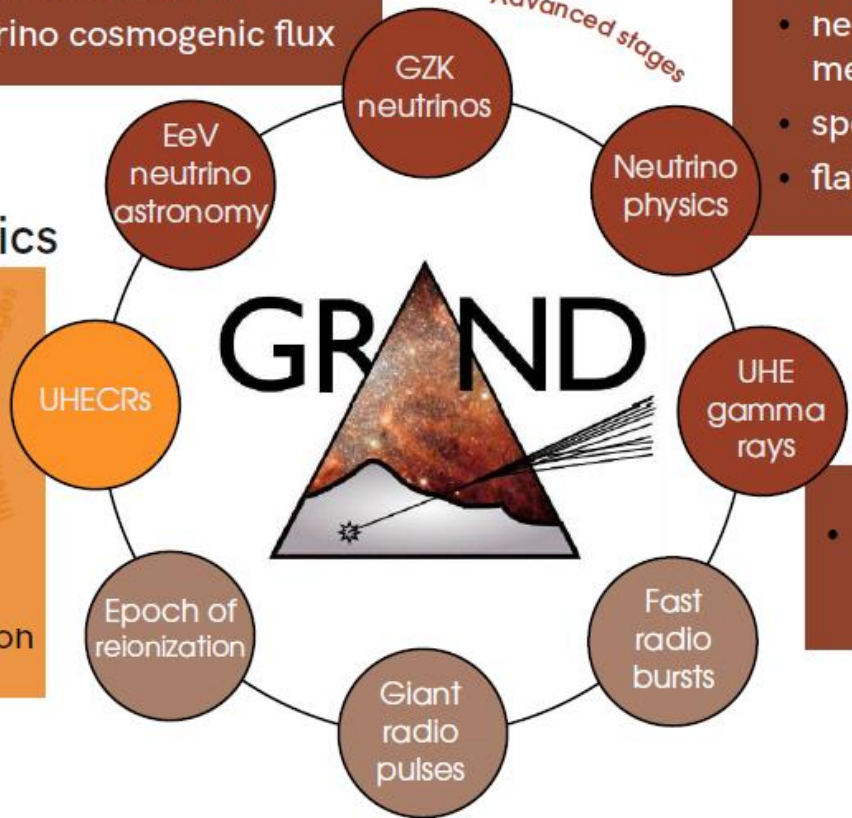
- UHE neutrino astronomy
- UHE neutrino cosmogenic flux

neutrino physics

- neutrino cross-section measurements
- spectral, angular distortions
- flavor ratios

UHECR, hadronic physics

- 20-80 times the exposure of Auger!
- GRANDProto300: transition from Galactic/ extragalactic
- hadronic physics: muon discrepancy, UHECR mass composition, p-air cross-section

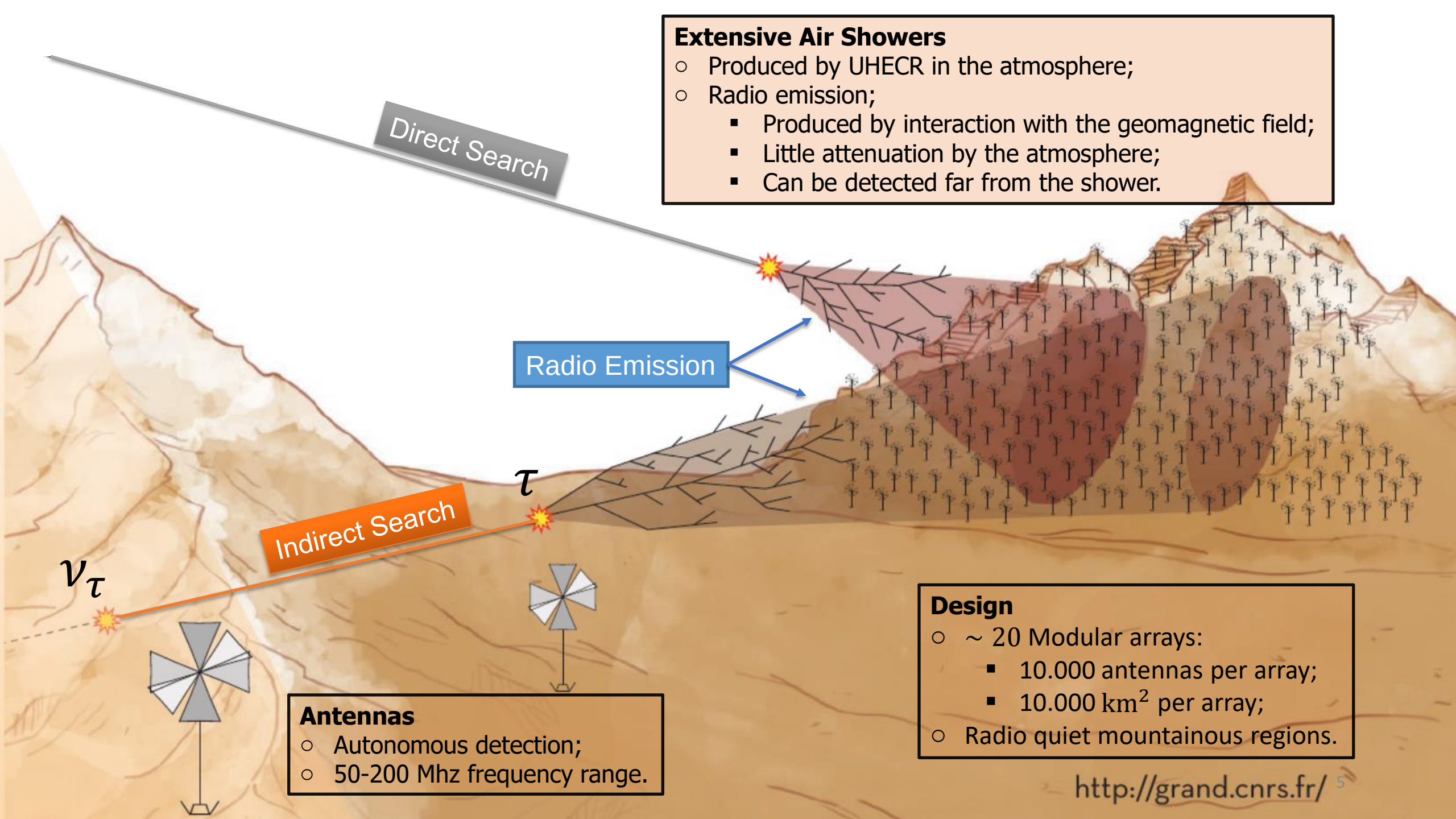


UHE gamma rays

- competitive with Auger at GRANDProto300 stage

radio-astronomy in a novel way

- unphased integration of signals: an almost full-sky survey of radio signals
- can detect FRBs and Giant Radio pulses of the Crab already at the GRANDProto300 stage



Extensive Air Showers
- Produced by UHECR in the atmosphere;
- Radio emission;
  - Produced by interaction with the geomagnetic field;
  - Little attenuation by the atmosphere;
  - Can be detected far from the shower.

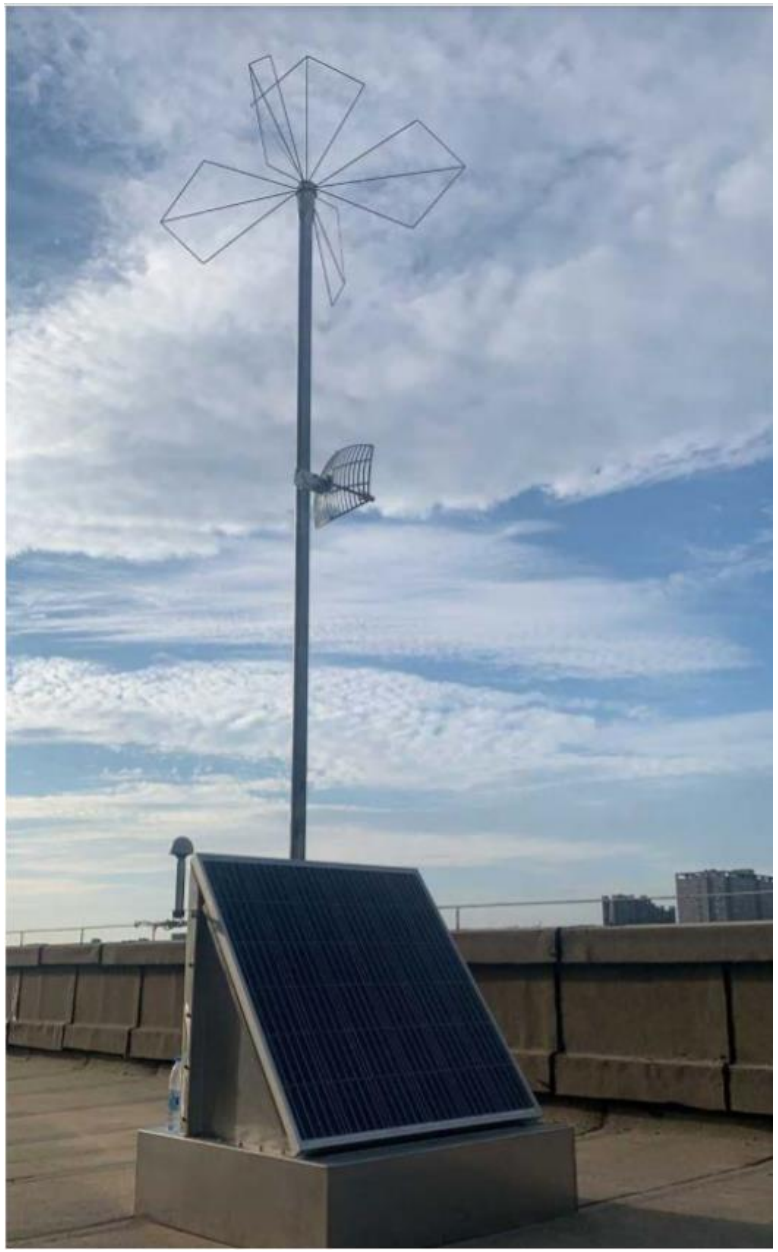
Antennas
- Autonomous detection;
- 50-200 Mhz frequency range.

Design
- ~ 20 Modular arrays:
  - 10.000 antennas per array;
  - 10.000 km^2 per array;
- Radio quiet mountainous regions.

http://grand.cnrs.fr/

Antenna design

- High detection efficiency along the horizon (HorizonAntenna);
- Placed $5\ \mathrm{m}$ above the ground (to reduce diffraction of radio waves off the ground);
- Bow tie design, flat response in azimuthal angle and frequency;
- Frequency range ($50\ \mathrm{MHz}$ - $200\ \mathrm{MHz}$):
  - $200\ \mathrm{MHz}$ improves the signal-to-noise ratio and lowers the detection threshold;
- Successfully tested in the field (Aug., Dec. 2018).



GRAND coll., Sci. China-Phys. Mech. Astron. (2020)

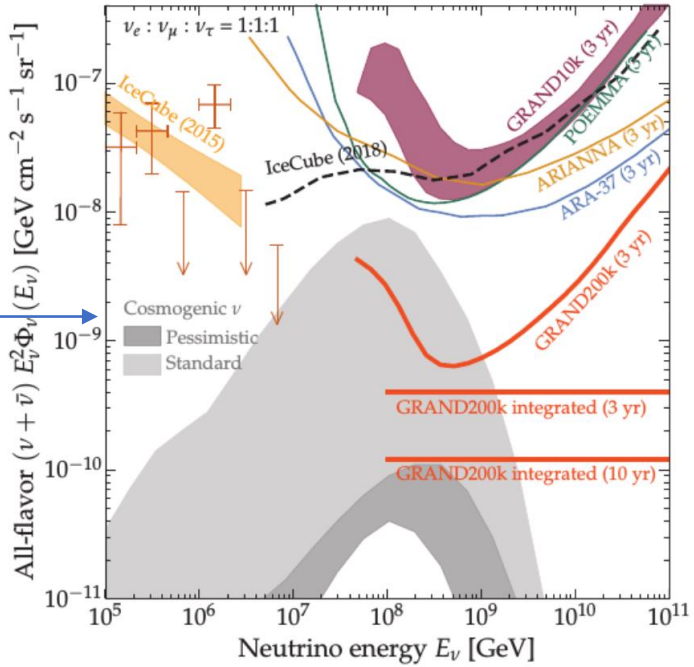
Alves Batista, R., **Lago, B.L.** *et al.* (2019)

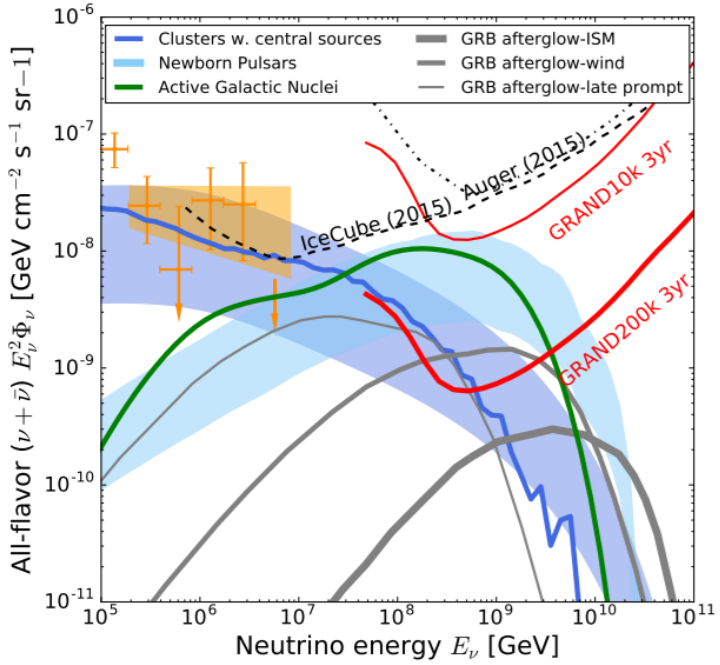
Ultra High Energy Messengers – ν

- Cosmogenic Neutrinos
  - Diffusive flux guaranteed to exist (UHECR + CMB or EBL);
  - Large spread in the predicted flux;

    Properties of the UHECRs, Distribution of sources, Neutrino emissivity of the source, UHECR injection spectrum, Mass composition of the injection at the source
- Neutrinos from sources
  - Diffusive flux produced at the sources;
  - GRAND could discover the first sources of UHE neutrinos at a significance of 5σ;
  - A promising way to identify EeV neutrino sources;

Detect transient neutrino emission in coincidence with electromagnetic emission. GRAND makes this possible, due to its excellent angular resolution and large sky coverage.





Ultra High Energy Messengers – ν cont.

Neutrino energy
Source-detector baseline
κ_n and n model-dependent

- Numerous new physics models have intensities $\sim \kappa_n E_\nu^n L$
- For EeV neutrinos GRAND is likely to probe
  - $\kappa_n \sim 4 \times 10^{-50} \left(\frac{E_\nu}{\mathrm{EeV}}\right)^{-n} \left(\frac{L}{\mathrm{Gpc}}\right)^{-1} \mathrm{EeV}^{1-n}$

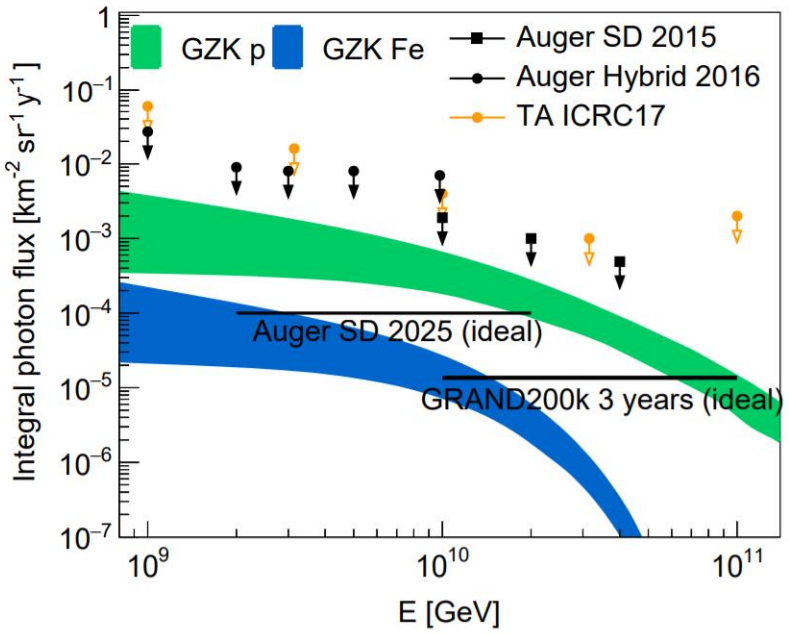
Examples
- $n = -1$ (neutrino decay)
- $n = 0$ (CPT-odd LIV)
- $n = 1$ (CPT-even LIV)

Atmospheric and solar ν
- $\kappa_0 \leq 10^{-32}\,\mathrm{EeV}$
- $\kappa_1 \leq 10^{-33}$

- Other observables sensitive to new physics
  - **Spectral shape**: spectral features, peaks, slope change. Benefits from GRAND's high statistics and energy resolution.
  - **Angular distribution**: extend measurements of neutrino-nucleon cross sections above PeV. Benefits from GRAND's sub degree angular resolution.
  - **Flavor composition**: Flavor ratios are free from relative uncertainties on the flux normalization. Benefits from GRAND's high sensitivity to ν_τ and cross analysis with other experiments.

Ultra High Energy Messengers – γ rays

GRAND coll., Sci. China-Phys. Mech. Astron. (2020)



- Cosmogenic UHE gamma rays are also guaranteed to exist, although not detected so far.

- Science Goals
  - Measure the flux of cosmogenic gamma rays above $10^{10}\,\mathrm{GeV}$ or strongly constrain it;
  - Gamma rays point back to their astrophysical sources:
    - GRAND could detect nearby sources of UHE gamma rays up to $10\ \mathrm{Mpc}$;
  - The detection of UHE gamma rays would probe the little known diffuse cosmic radio background (CRB)
    - GRAND could be the first experiment to put such indirect constraints on the CRB with its full efficiency for photon detection in the energy range from 10^{10} to $10^{11}\ \mathrm{GeV}$.

Ultra High Energy Messengers – Cosmic rays

- GRAND statistics
  - Precise shape of the cutoff ($\sim 4 \times 10^{10}$ GeV) → source out of power or GZK process;
  - Fully efficient for cosmic rays with $\mathrm{E} > 10^{10}$ GeV and zenith-angle $65° \leq \theta \leq 85°$
    - Aperture of $107\,000$ km^2 sr → Exposure of $535\,000$ km^2 sr yr after 5 years
      - Around $32\,000$ events with energies above $10^{10.5}$ GeV.
- Mass composition
  - Key to understand the galactic to extragalactic transition (ankle of the spectrum);
- Arrival directions
  - Benefits from high statistics; Full sky coverage; TA hotspot and Auger dipole within the field of view;
- Proton air cross section
  - Large statistics could extend current measurement up to $\sqrt{s} \sim 2 \times 10^5$ GeV.

Ultra High Energy Messengers – Multi

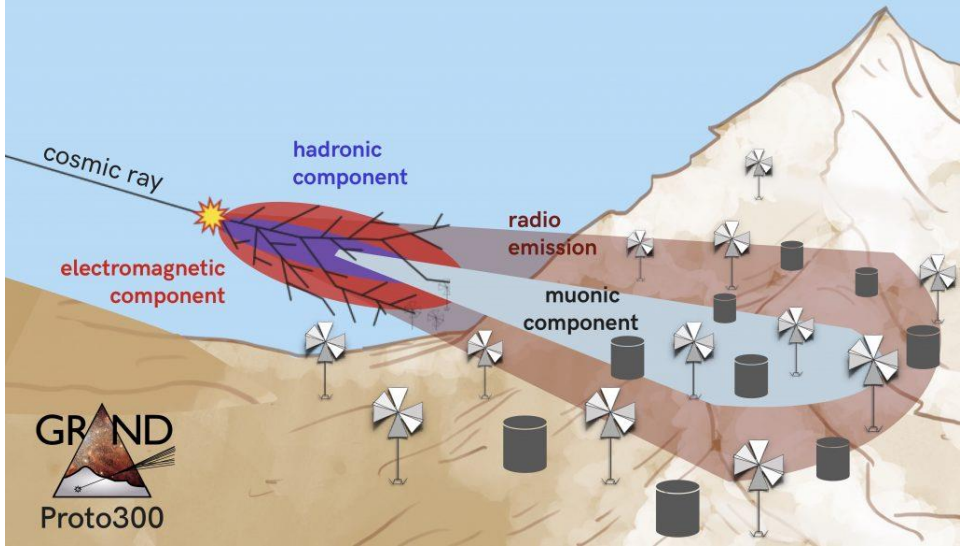
- By the time GRAND reaches its later stages:
  - Multi-messengers available: neutrinos, cosmic rays, photons, and gravitational waves
  - Future experiments will observe mergers from cosmological distance and have a wide coverage of the electromagnetic spectrum.
- UHE neutrinos from transient point sources + electromag. observations
  - GRAND's sub degree angular resolution + timing → pinpoint neutrino sources from galaxies in the field of view.
- UHE gamma rays from transient point sources
  - GRAND γ-rays + CTA synchrotron (γ-ray + LSS around source -> E.M. cascade);
  - γ-rays from short GRB + gravitational waves (emitted hours or days earlier).
- Due to its unprecedented UHE neutrino sensitivity, GRAND will be a crucial triggering and follow-up partner in multi-messenger programs

A staged approach with self-standing pathfinders

Slide by Kumiko Kotera

	GRANDProto300	GRAND10k	GRAND200k
	2021	2025	203X
Goals	**autonomous** radio detection of **very inclined** air-showers **cosmic rays $10^{16.5\text{-}18}$ eV** • Galactic/extragalactic transition • muon problem • radio transients	**1st GRAND sub-array** • **discovery of EeV neutrinos** for optimistic fluxes • radio transients (FRBs!)	sensitive **all-sky** detector **1st EeV neutrino detection and/or neutrino astronomy!**
Setup	• 300 HorizonAntennas over 200 km^2 • Particle detectors (a la HAWC/Auger) • Qinhai Province, China	• 10,000 radio antennas over 10,000 km^2 • in China	• 200,000 antennas over 200,000 km^2 • 20 sub-arrays of 10k antennas • on different continents
Budget	**2 M€** 100 antennas already paid (China)	**13 M€** 1500€/unit confident for large contribution from China	**300M€** in total 500€/unit to be divided between participating countries

GRANDProto300



- A 300-antenna pathfinder stage of GRAND;
  - $200\ \mathrm{km}^2$ area;
  - 100 antennas ready to be deployed;
- Aims to validate the GRAND as a standalone radio detection array and realize the self-trigger techniques;
- A test bench to improve:
  - Angular, energy and mass composition reconstruction;
- Detection of very inclined cosmic rays with energies from $30\ \mathrm{PeV}$ to $1\ \mathrm{EeV}$;
  - Study the galactic to extragalactic transition energy range;
- Potential sensitivity for radio transients such as Giant Radio Pulses and Fast Radio Bursts.

Summary

- GRAND key features:
  - The largest UHE observatory -> improved statistics with full sky coverage;
  - Modular design using relatively inexpensive antennas;
  - Rich Science case;
- Test fundamental physics using:
  - Cosmic rays;
  - Cosmogenic neutrinos;
  - Cosmogenic gamma rays;
  - Multi-messengers;
- GRANDProto300 will serve as a path finder
  - Study the galactic to extragalactic transition;
  - Will begin operation soon.