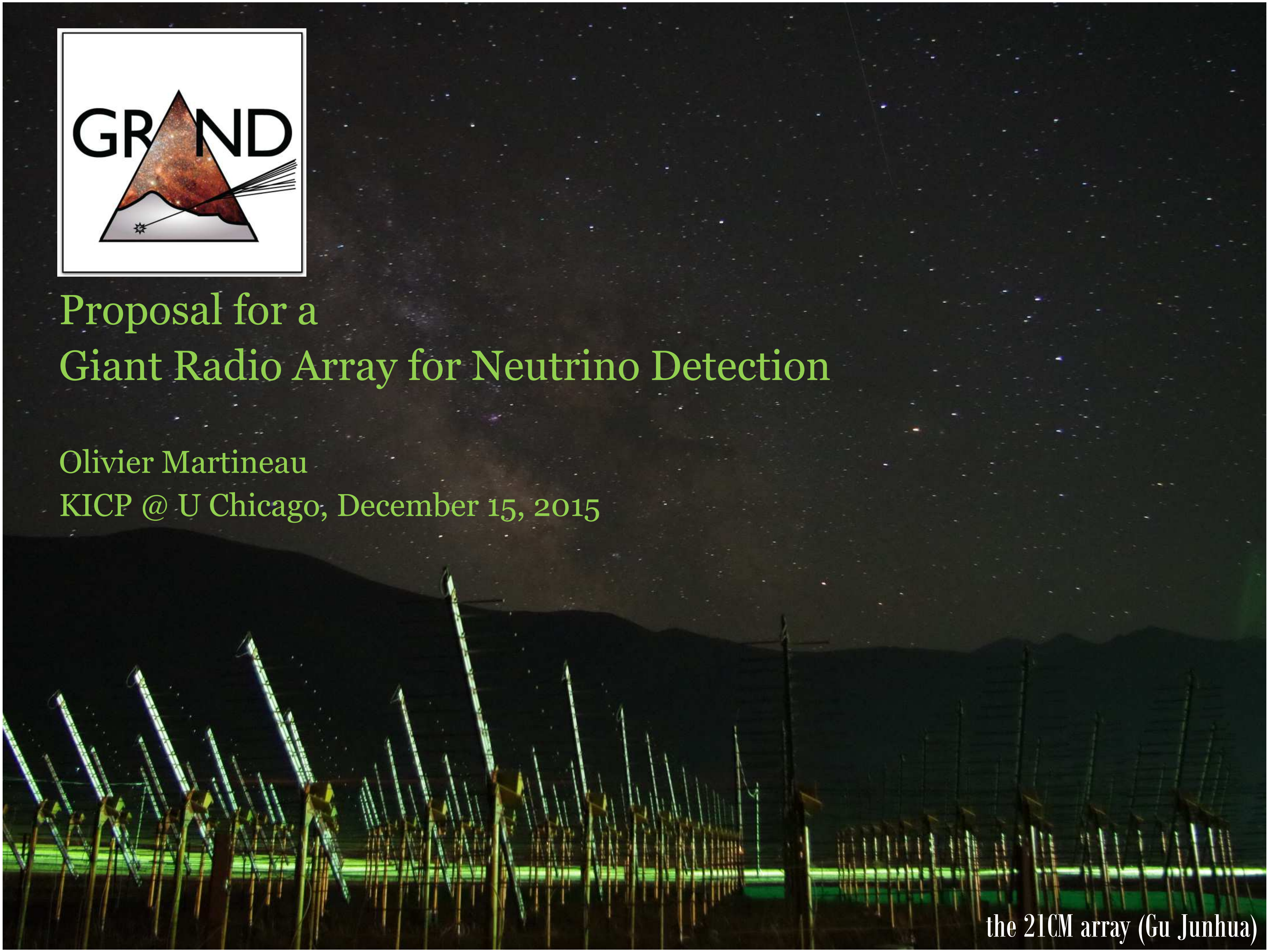
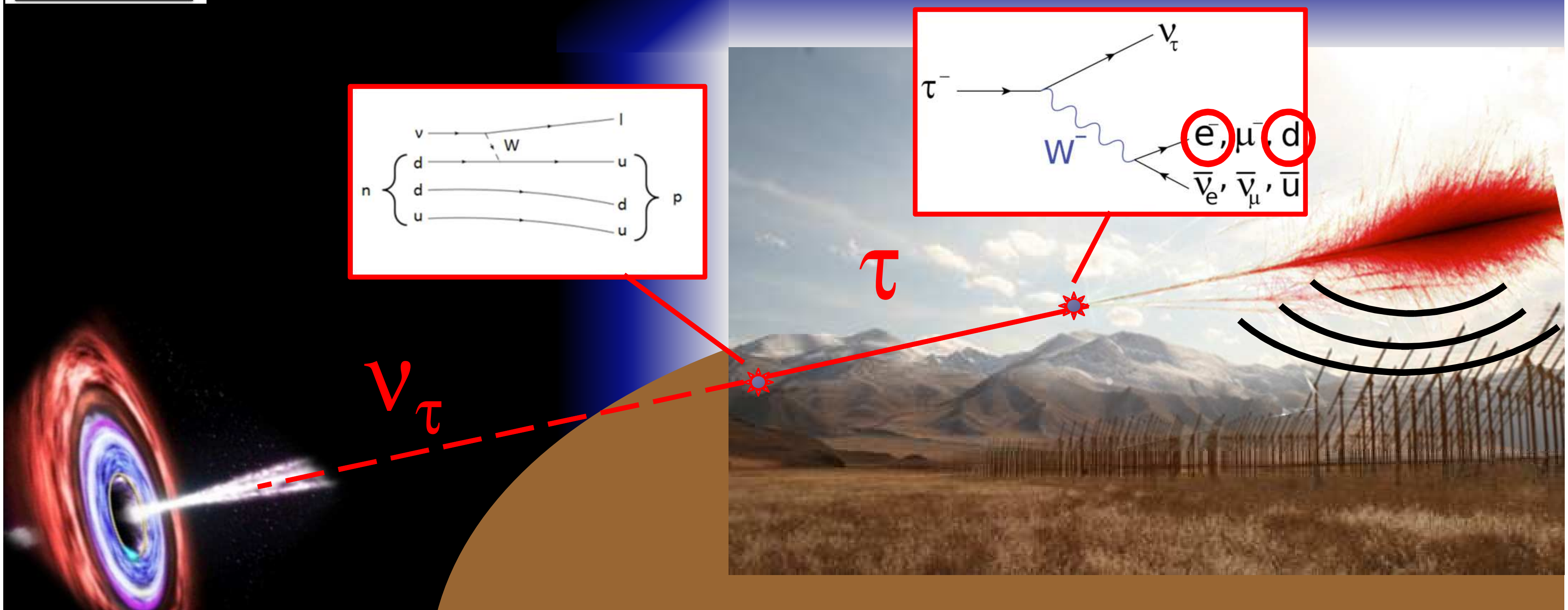
Proposal for a Giant Radio Array for Neutrino Detection

Olivier Martineau
KICP @ U Chicago, December 15, 2015



the 21CM array (Gu Junhua)

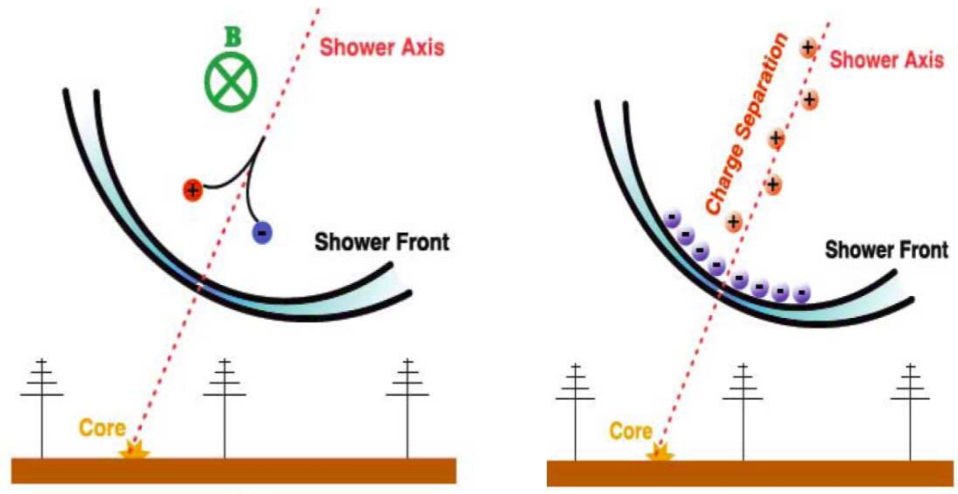
GRAND detection principle



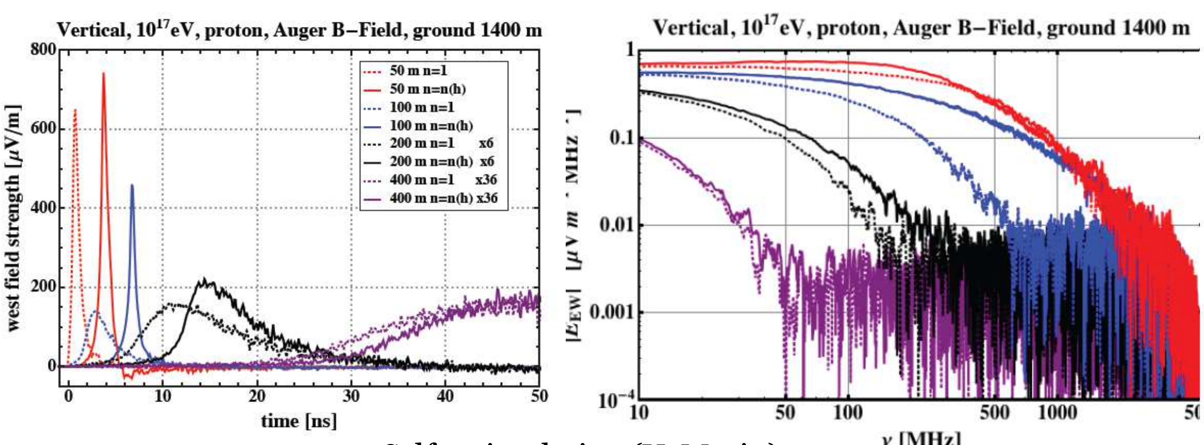
- Goal: search for cosmic neutrinos
- Detection principle:
  - ν-induced tau decay in atmosphere generates ~horizontal extensive air showers.
    [Fargion astro-ph/99066450, Bertou astro-ph/0104452]
  - Subsequent EAS radio-detection

EAS radio emission

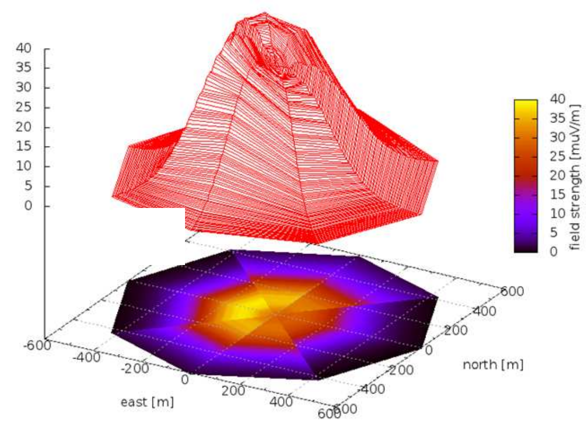
- Production mechanism: geomagnetic effect
  (+ charge excess)



- Transient (<100ns), beamed emission, coherent in 10-200MHz.
- Flat wavefront, amplitude scales linearly with energy.

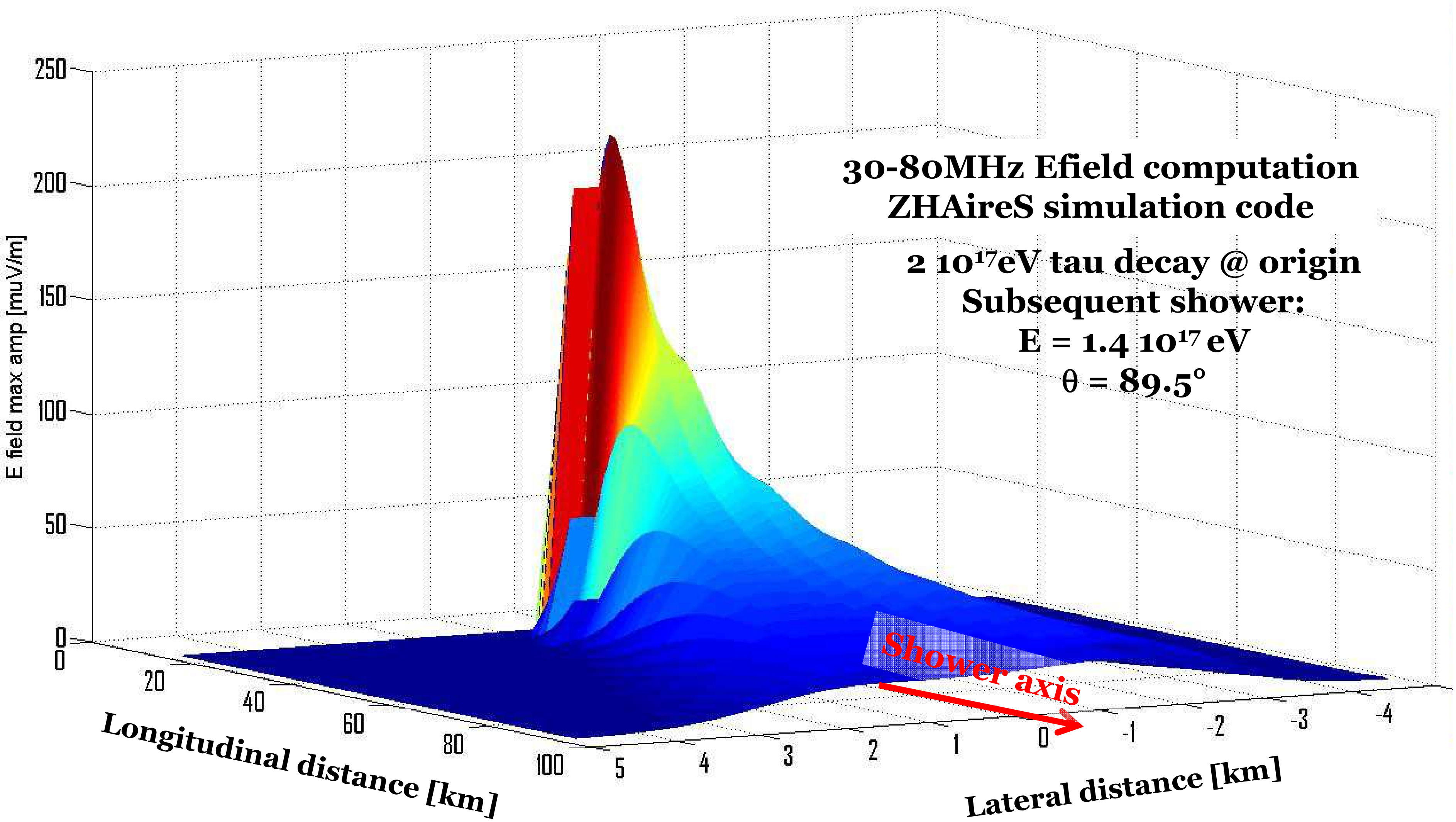


Selfas simulation (V. Marin)



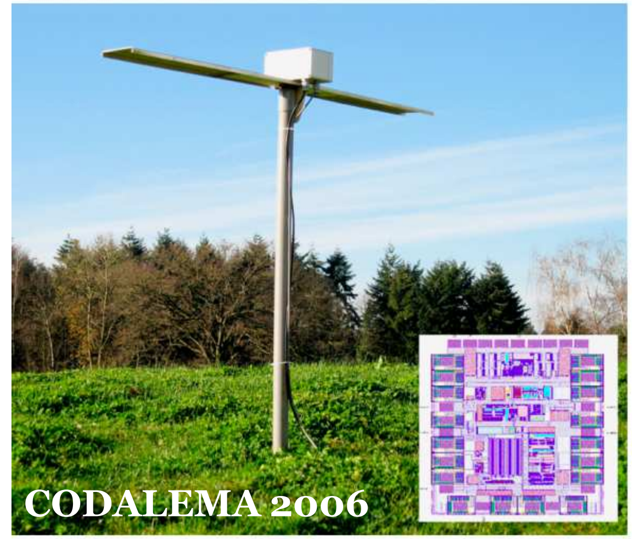
CoREAS simulation (Huege)

(Very) inclined EAS radio detection



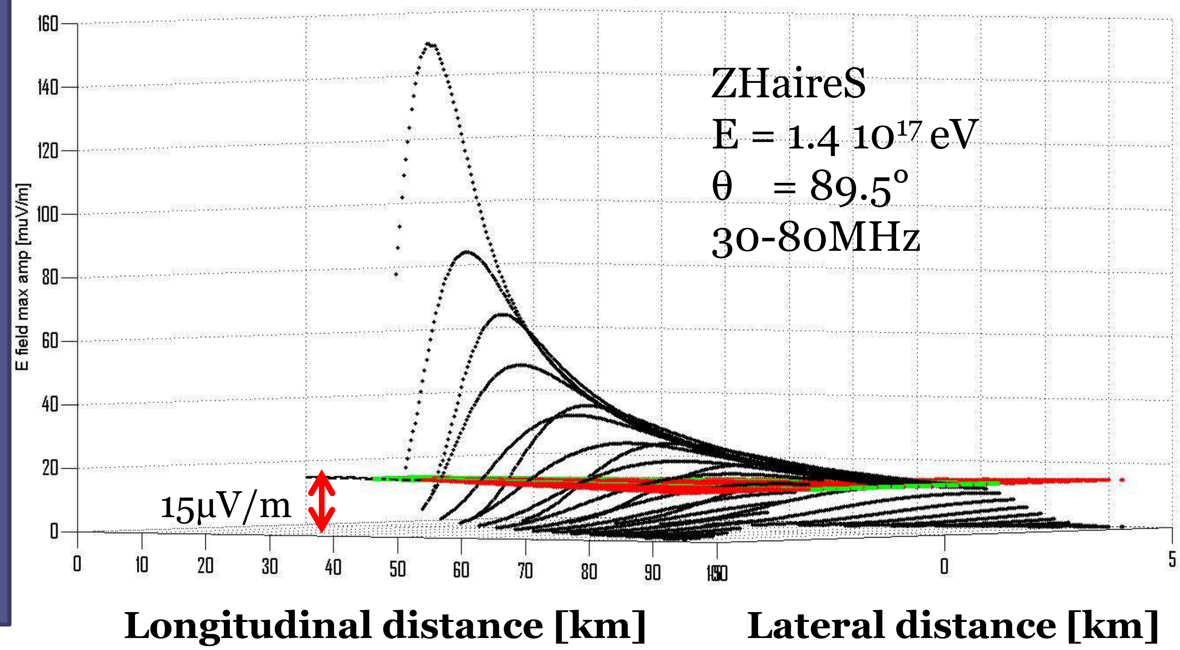
EAS radio detection

- Radio antenna are basic detectors, benefiting from extensive technical developments (☆large band & large field of view)
- Fast electronics (>100MHz) easily available.
- Atmosphere transparent to radio waves.
- Short waves prevent detection below 25MHz.
- Sky noise level: **rms ~15µV/m** for 30-100MHz



- Radio antennas well suited to very large arrays.
- Efield emitted by horizontal EAS still in detection range after 100km+ for E>2 10^{17}eV.

⇨Radio antennas well suited for ν-induced EAS!
[Brusova et al. <0708.3834>]



GRANDproject genesis

- TREND proposed in 2008 with P. Lautridou & D. Ardouin (Nantes) (Ardouin et al. <1007.4359>)
- 1st goal: autonomous EAS radio detection & identification.
- Small team: NAOC (Wu XiangPing + 2), IHEP (1), OM (@Beijing, 2009-2013) & V. Niess

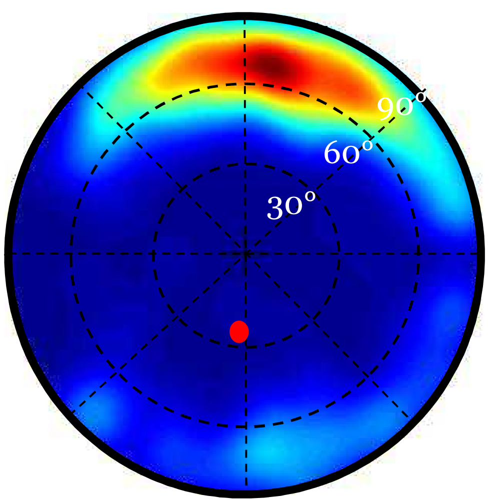
Zhao Meng, Wu XiangPing, P. Lautridou, D. Charrier & D. Ardouin Nantes, April 2008

TREND site, October 2008

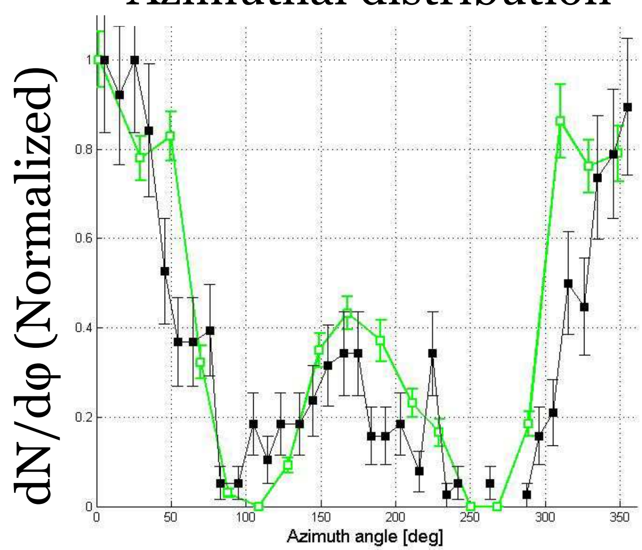
TREND-50 (2011-2014)

- Site: Ulastai, XinJiang province, China (site of the 21CMA radio-interferometer)
- 50 monopolar antennas deployed over 1.5km²
- **DAQ allowing ~200Hz trigger/antenna**

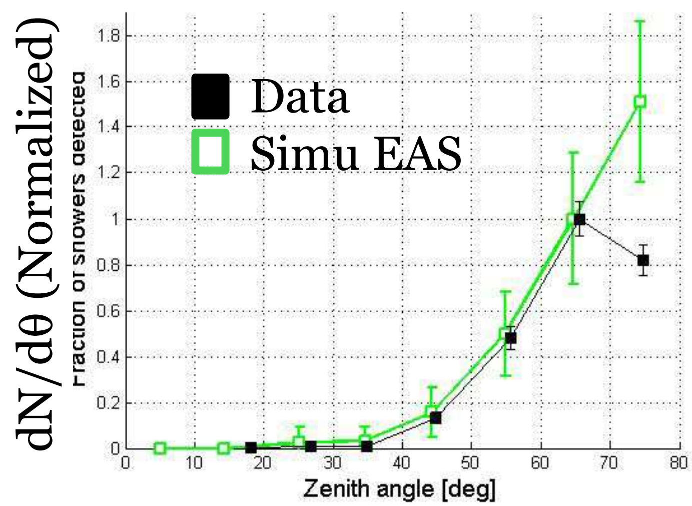
TREND: 465 EAS candidates selected in 317 live days from offline analysis of radio data. Distribution as expected for EAS ⇨ **TREND goal reached:** autonomous EAS detection & identification with radio antennas is possible.



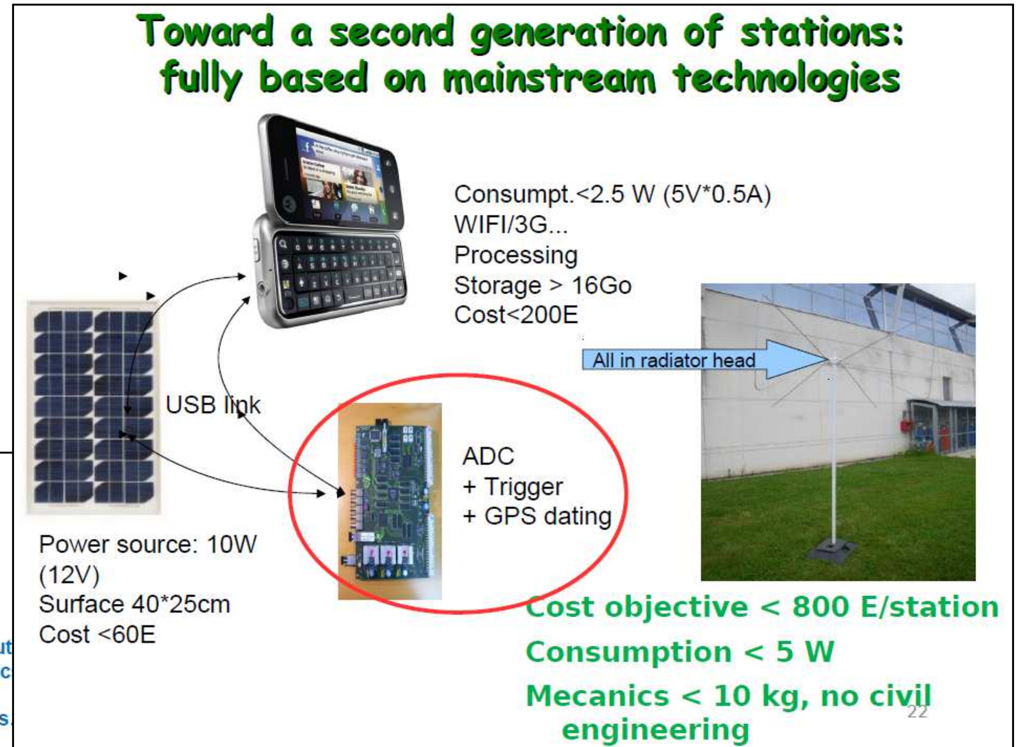
Azimuthal distribution

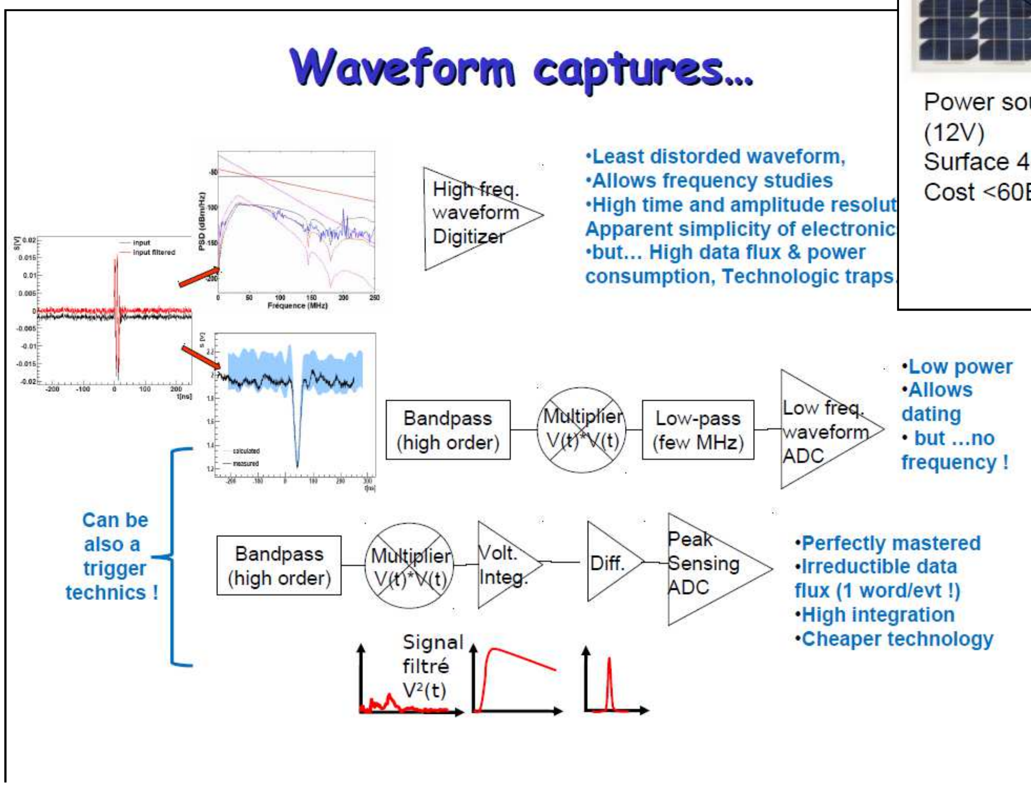


Zenithal distribution



EAS radio detection unit





P. Lautridou
GHz workshop, Clermont-Ferrand
January 2011


Let’s not be shy… and go for a GIANT array!

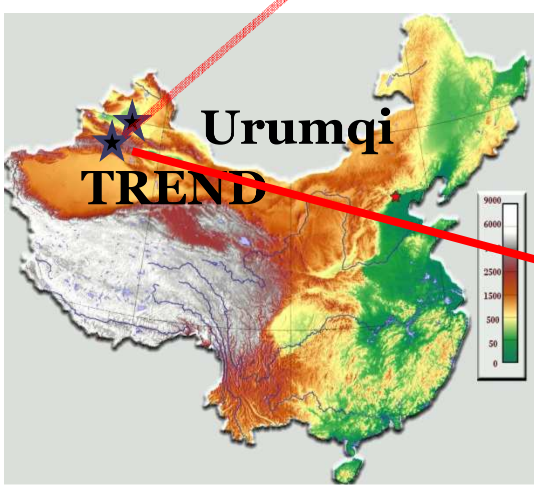
GRAND check list

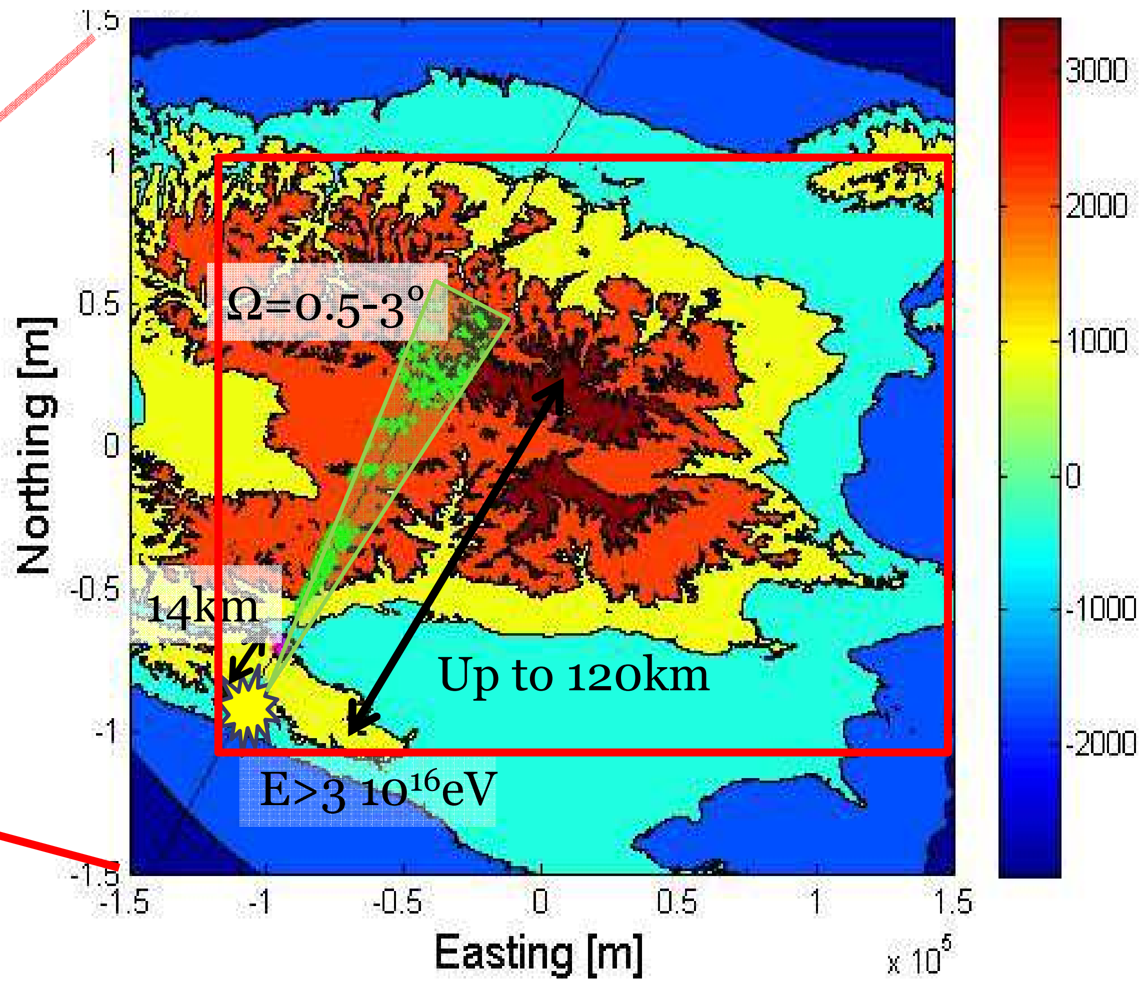
- How about a (really) GIANT array?
  - Expected performances?

GRAND ν sensitivity study - Setup

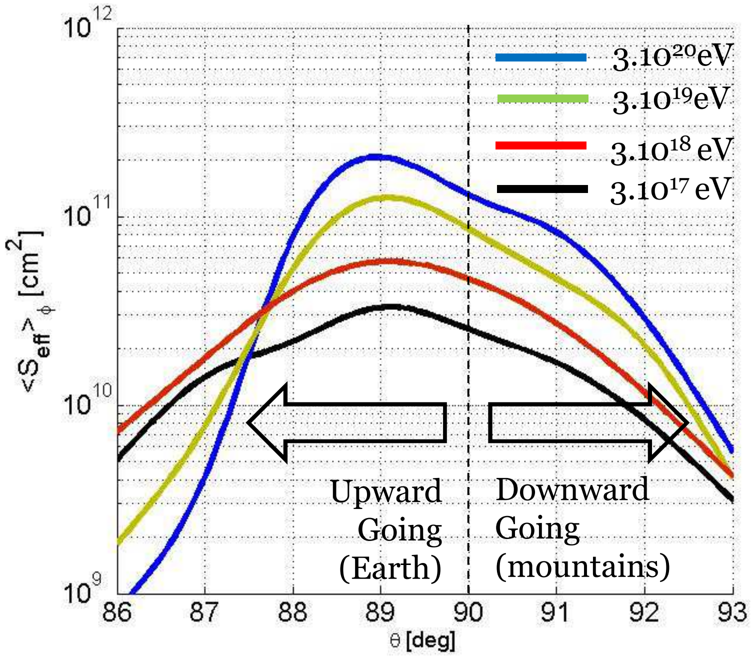
Preliminary study: 60000km²

- MC down to τ decay (E_ν in 10^{17} - 10^{21} eV, θ in [85-95°])
- Simplified criteria for subsequent shower detection:
  - Antenna fired if:
    - in direct view of shower
    - in a light cone of few degs (Ω=f(E), [0.5-3°])
    - Tau decay point distant by [14-120] kms.
  - Shower detected if one cluster of 8+ antennas fired.
- Simulation array= ~90000 antennas over 220x270~60000 km² in Tianshan mountains (800m step size).





GRAND ν sensitivity study - Results

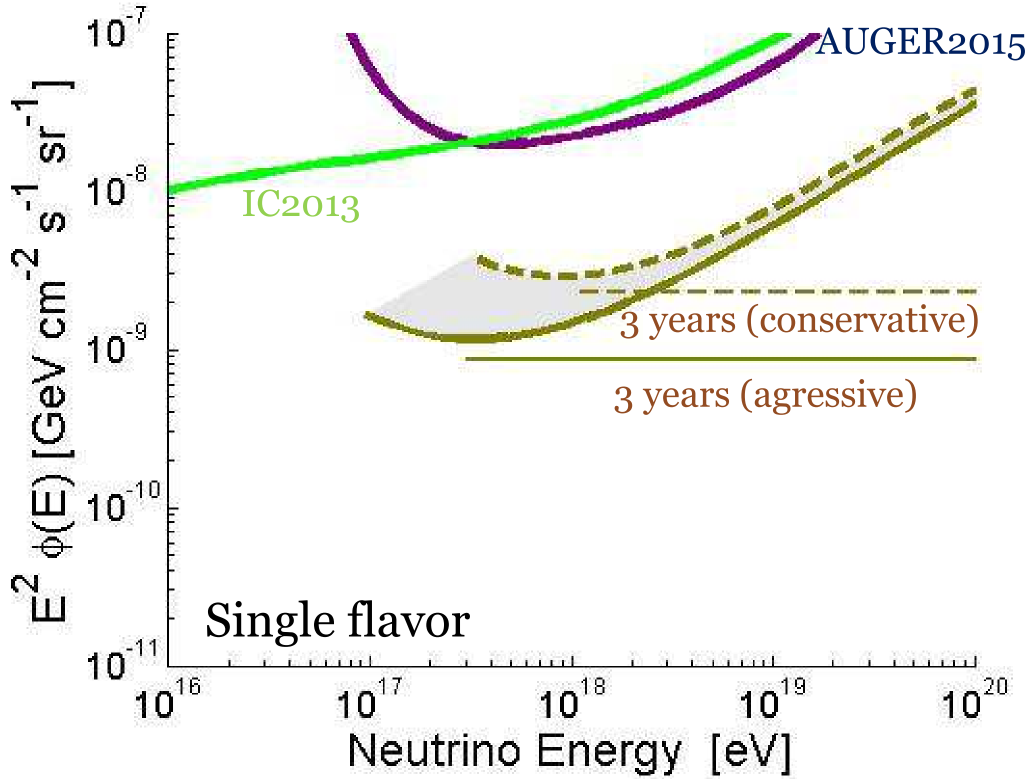


- Sensitivities > 0 for zenith values = ±4° around horizontal ⇨ Earth-skimming trajectories only.
- Mountains are sizable tragets (~40% of total).
- Earth becomes opaque at higher energies

- 60'000km² simulation setup
- single flavor flux $\phi(E)= \phi_0 E^{-2}$
- no candidate in 3 years

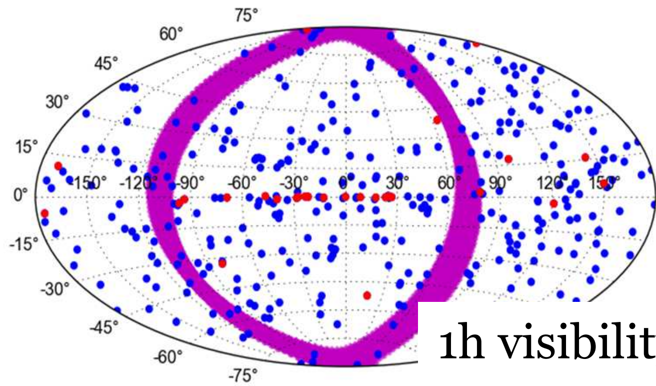
⇨ 90% CL integral limit:

$\phi_0 < 8\ 10^{-10} - 2\ 10^{-9}$ Gev/cm²/sr/s

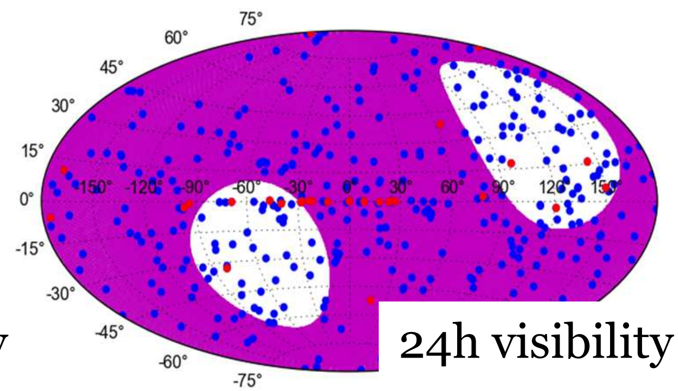


GRAND ν sensitivity study - Results

- Field of view

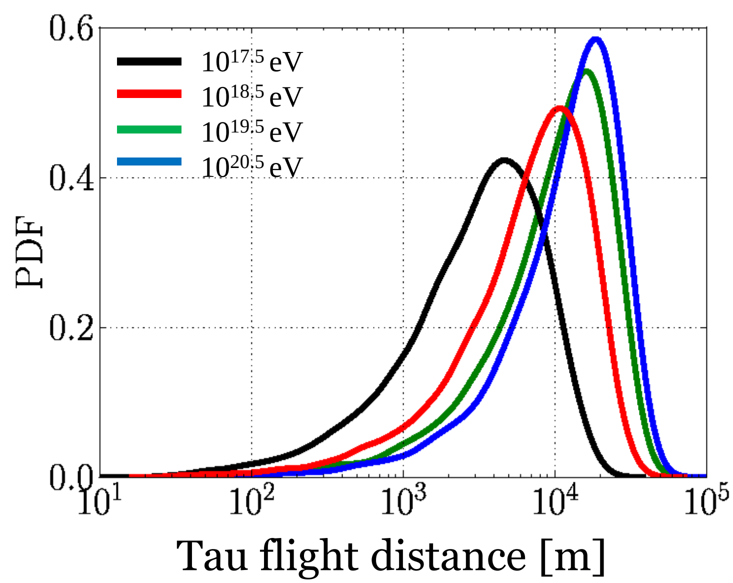


1h visibility

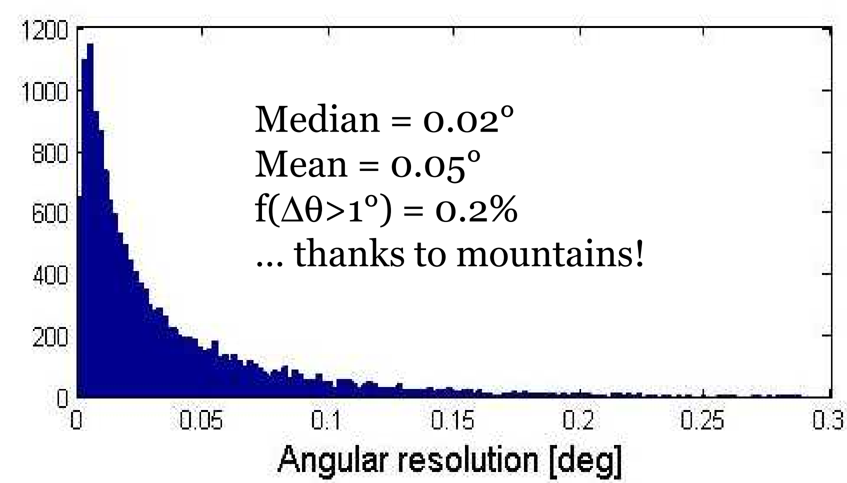


24h visibility

- Energy reconstruction
  - ... is not possible
  - But at least we know $E_\nu > E_{sh}$
  - Do better thanks to E_ν correlation with τ time of flight (?)



- Angular resolution
  - Computed analytically for all detected showers in simulation from Ardouin et al., arxiv/1007.4359, assuming 3ns trigger timing precision.
  - Mean = 0.05°: full benefit of extended trigger zone.



GRAND check list

- How about a (really) GIANT array?
  - Expected performances are promising!
  - Science case?

Cosmogenic neutrinos

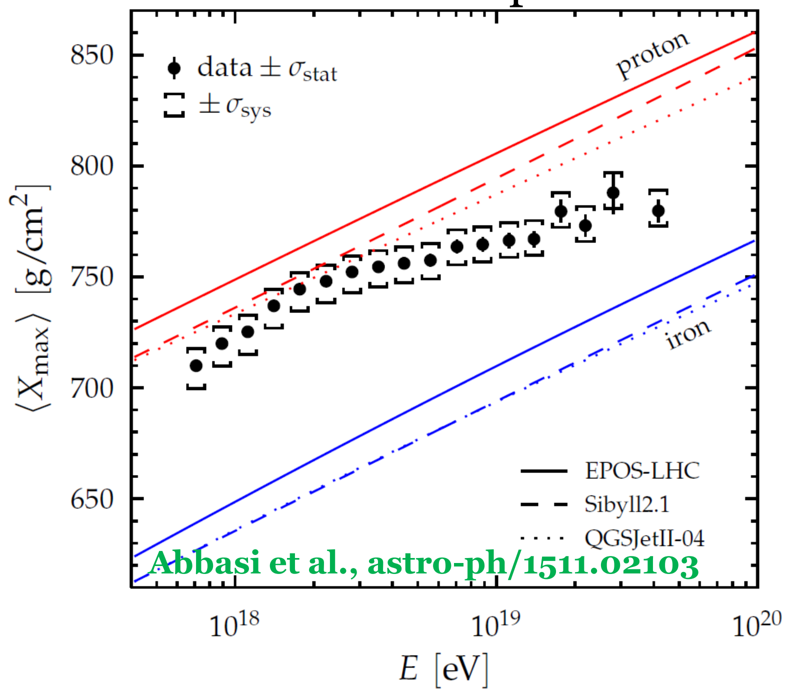
- GZK neutrinos above $10^{19.5}$eV:

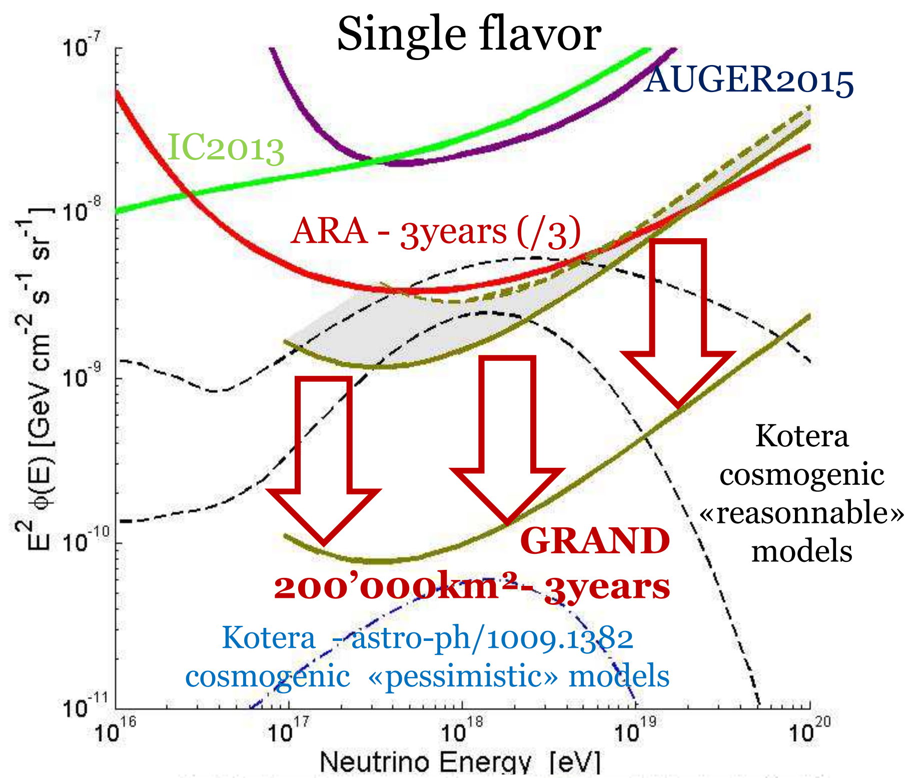
$p+\gamma_{CMB} \longrightarrow \Delta^{+} \longrightarrow \pi^{+} + n$

$\pi^{+} \longrightarrow l + \nu_{l}$

Guaranteed flux.
Great tool to study UHECRs.

AUGER composition

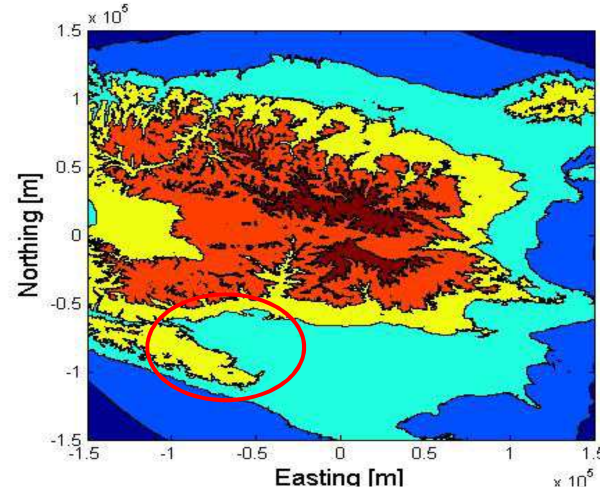


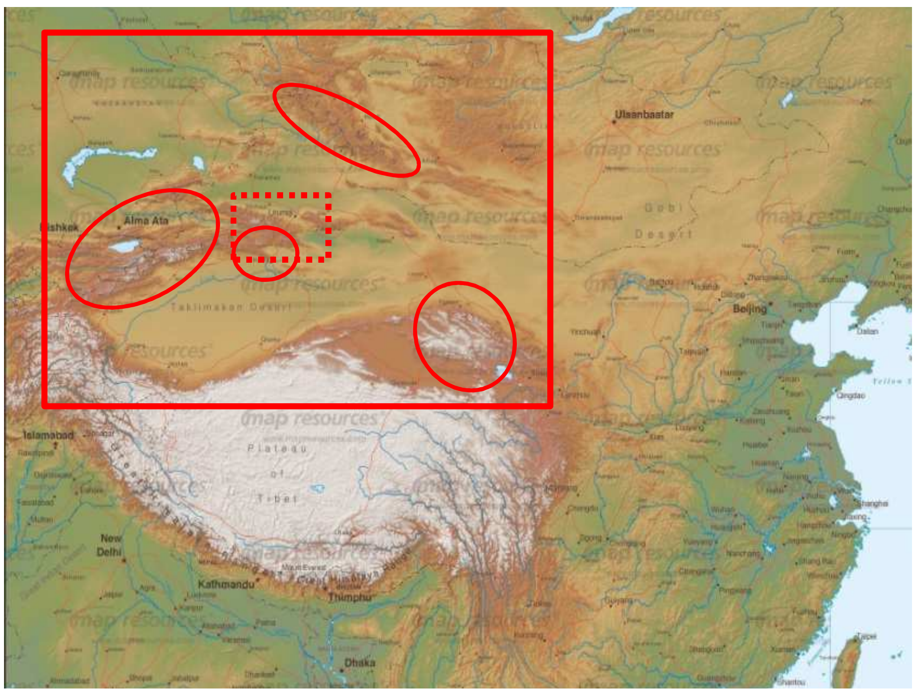


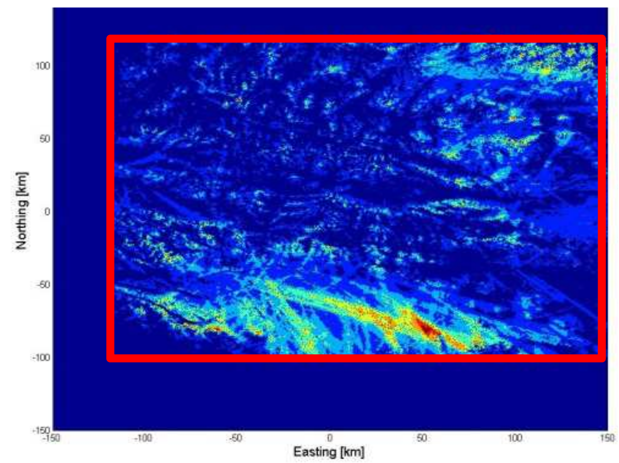
Output of GRAND 1st workshop
(LPNHE, Feb. 2015):
GRAND should GUARANTEE detection of cosmogenic neutrinos
(and rate of several tens/year for reasonnable models)

GRAND ν sensitivity study

- Target sensitivity: $\phi_0 = 5\ 10^{-11}$ GeV/cm²/sr/s (~10 times better than 60000km²)
- Driver: go for hotspots! Then 200000km² may be enough to reach target sensitivity
- Giant simulation area (1'500'000 antennas over 1'000'000 km²?) to identify hotspots.





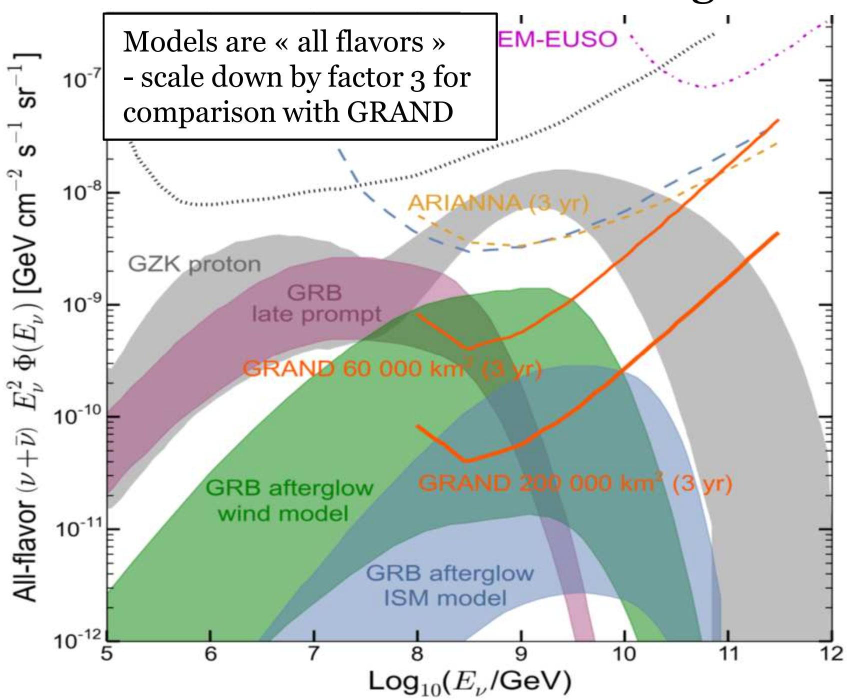


Hotspot with favorable topology
⇒ enhanced detection rate!
x 10 in sensitivity for x 3 in surface(?)

Neutrino astronomy

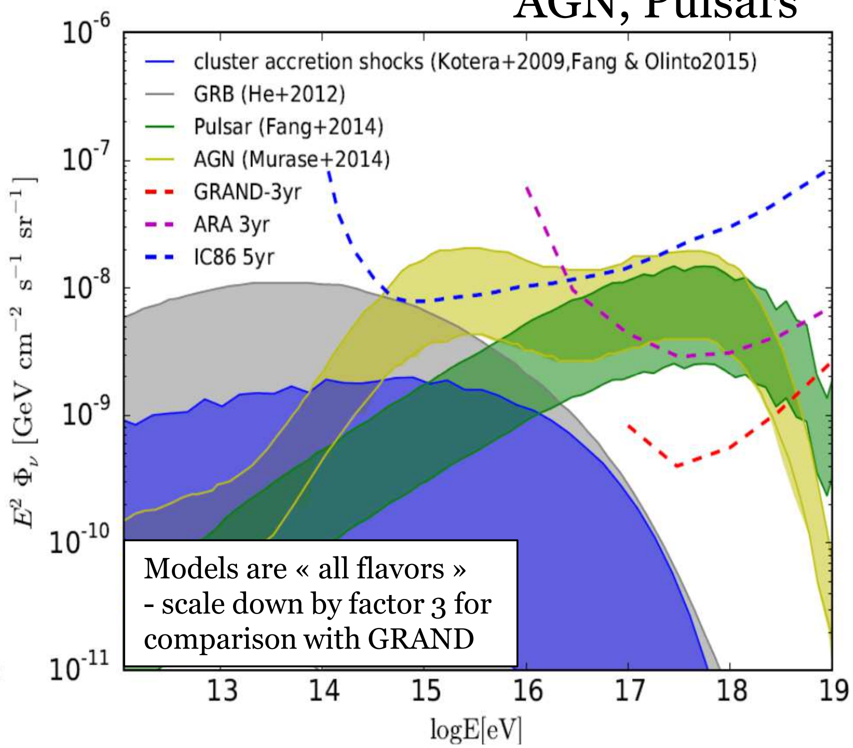
- Study of populations, transient or individual violent sources (AGNs, GRBs, pulsars, etc.)
- Possible if GRAND expected sensitivity & angular resolution is reached.

GRB afterglows



Murase., astro-ph/0707.1140

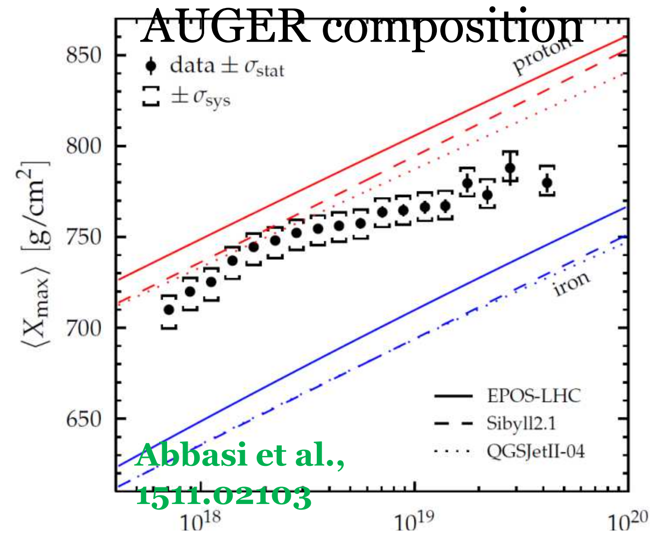
AGN, Pulsars

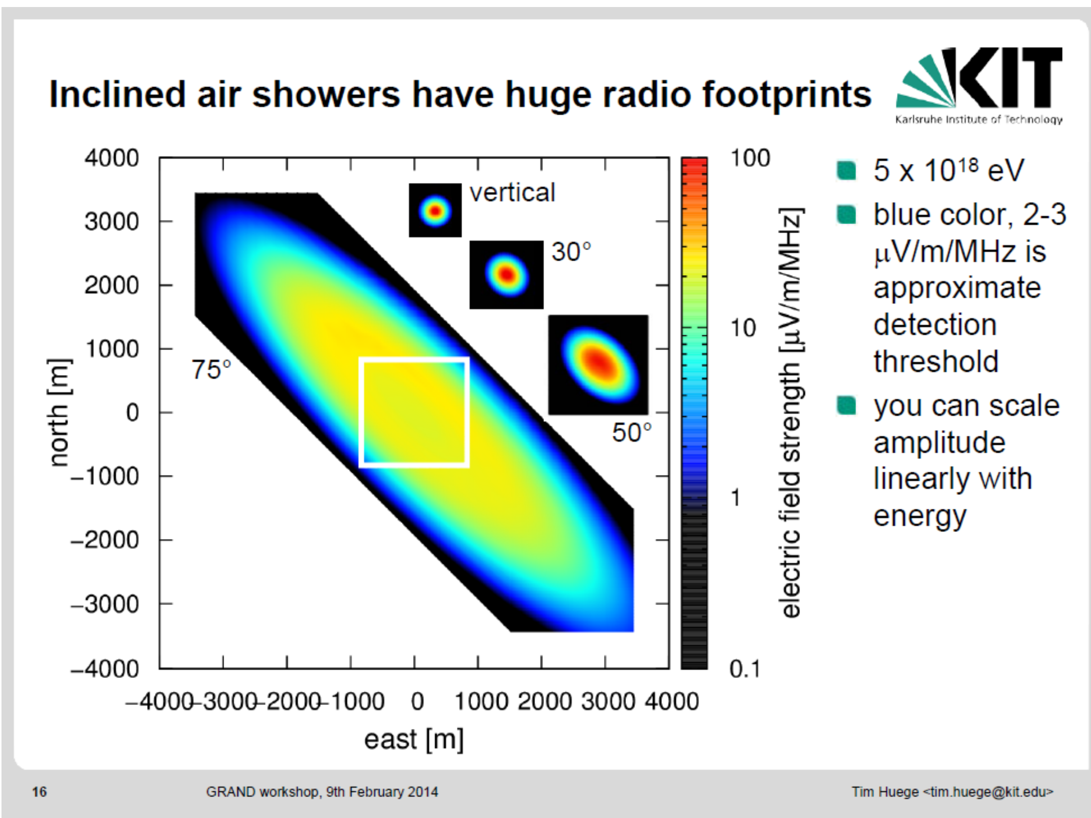


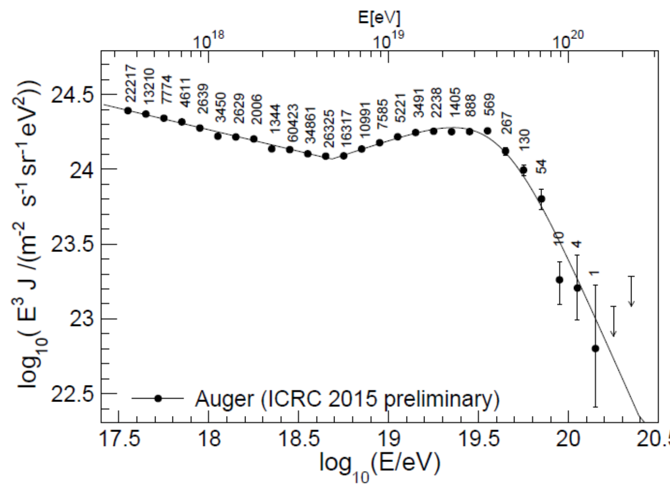
Fang et al., astro-ph/1311.2044

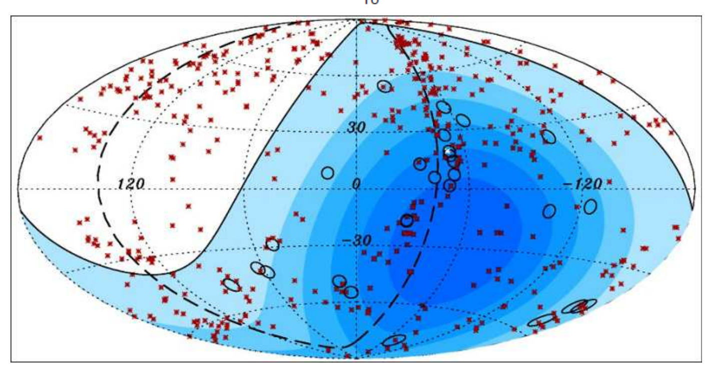
Trans-GZK UHECRs

- Significant stat achievable thanks to huge detection area (AUGER x 60)… very valuable if competitive composition measurement





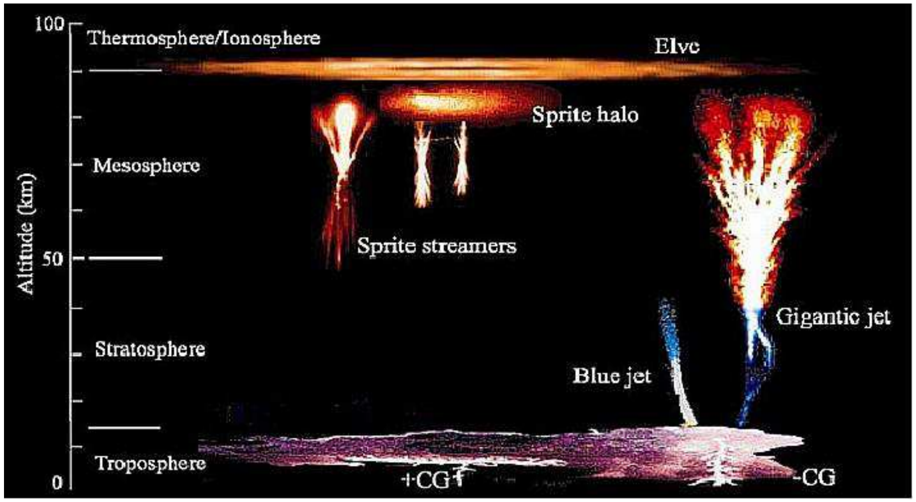




GRAND science case

- Help find & study sources of violent phenomena in the Universe through HE cosmic particle detection.
  - Cosmogenic neutrinos
  - Neutrino astronomy
  - Trans-GZK UHECRs

- Other topics
  - Epoch of Reionization
  - Fast Radio Bursts
  - Extreme electromagnetic atmosphere events (Elfs, Sprites, etc.)



- **GRAND could be a great tool for HE astrophysics (if …), it already generates significant excitment in the community.**

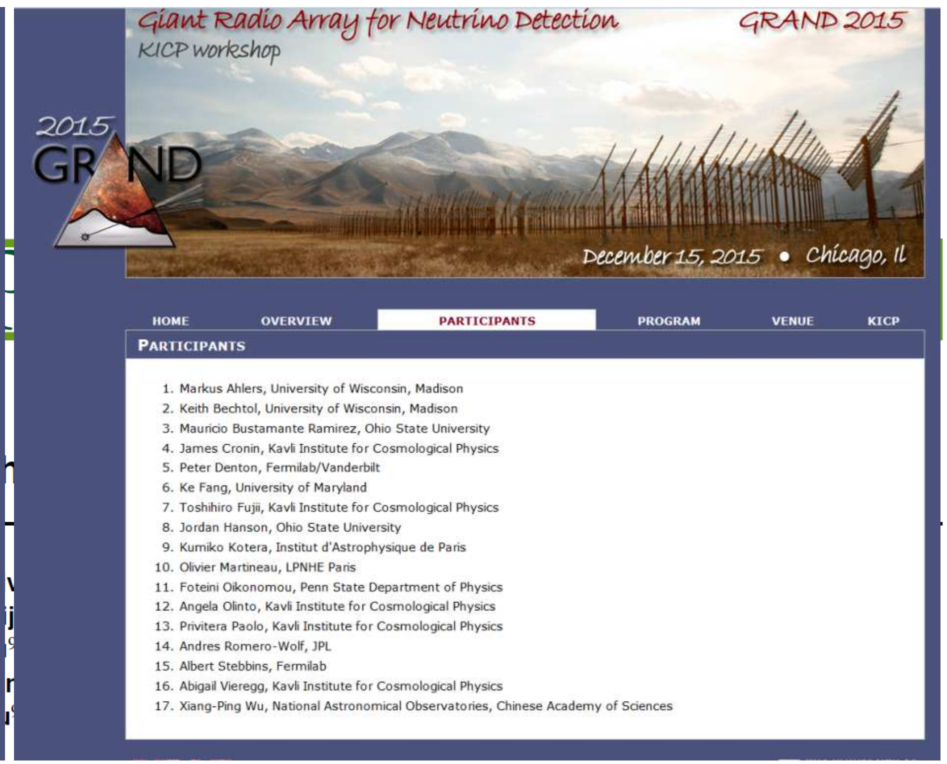
- **«White paper » to be written within 1.5 years.**

GRAND check list

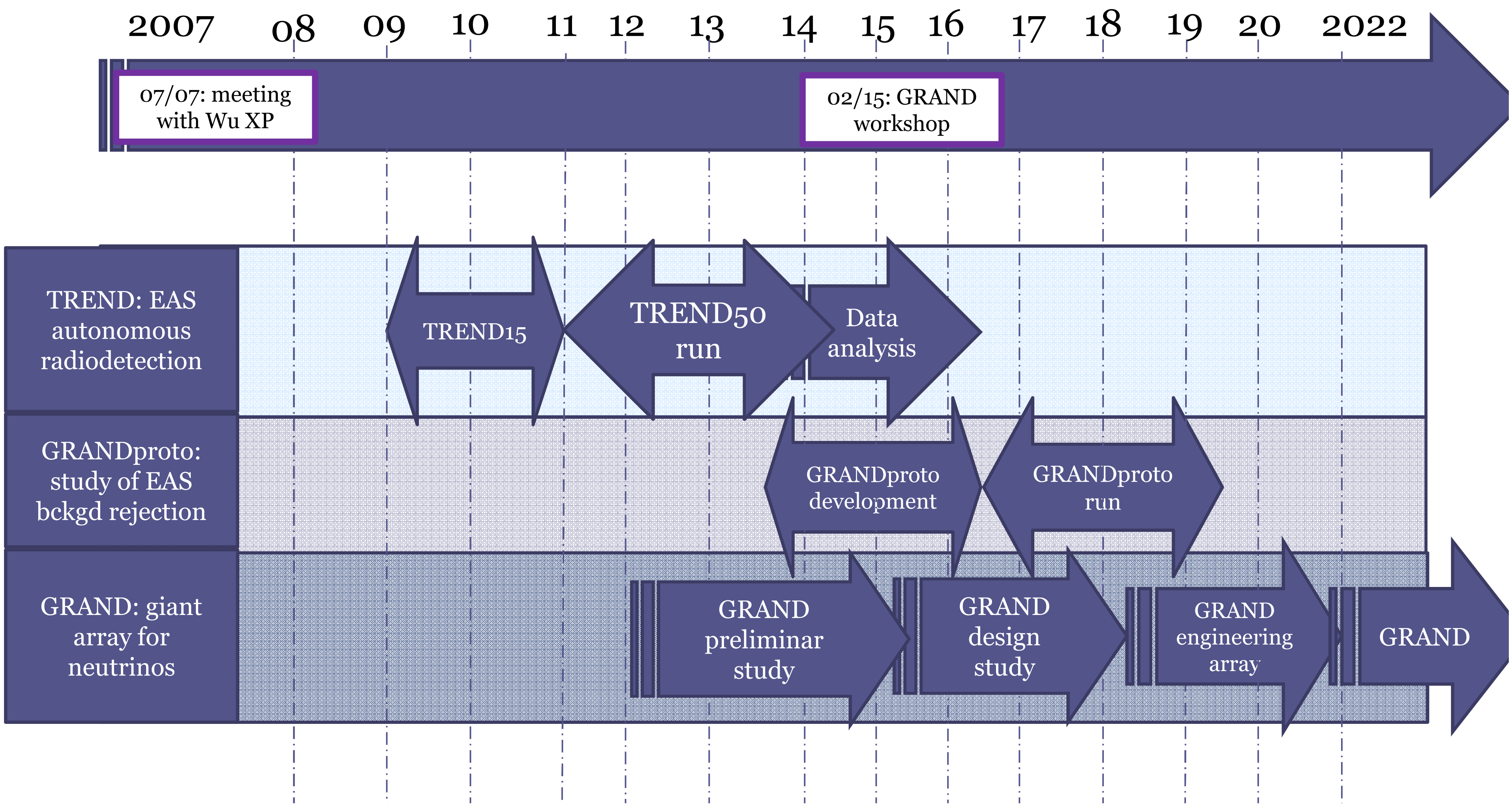
- How about a (really) GIANT array?
  - Expected performances are promising!
  - Science case is exciting!
  - Potential issues/ To do list?
    - Ground reflexion could be an issue
    - Rigorous simulation: on the way
    - Background rejection: GRANDproto
    - Technological challenges: leads to explore

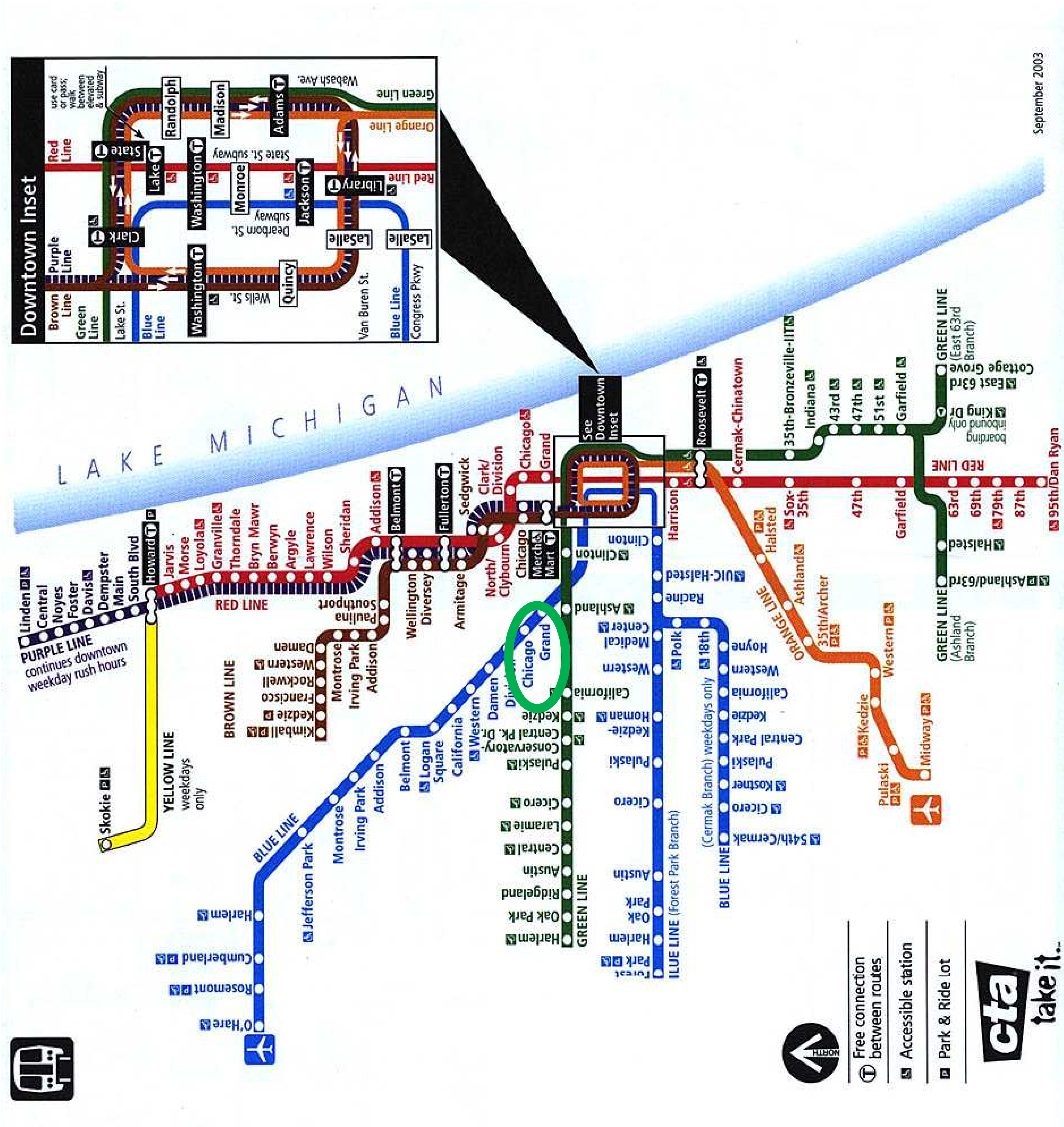
GRAND people

- GRAND study initiated (2012-2014) with very limited ressources (OM+ V. Niess for ν sensitivity study, K. Kotera for science case)
- Seminal ILP workshop @ LPNHE (Feb. 09-11, 2015)
  - 38 participants (AUGER, IceCube, ANITA, ARA, …)
  - Define GRAND strategy: ambitious VHE neutrino astronomy + post-AUGER program
  - Interest raised, individuals getting involved.
- Work getting organised!



(Tentative) timeline

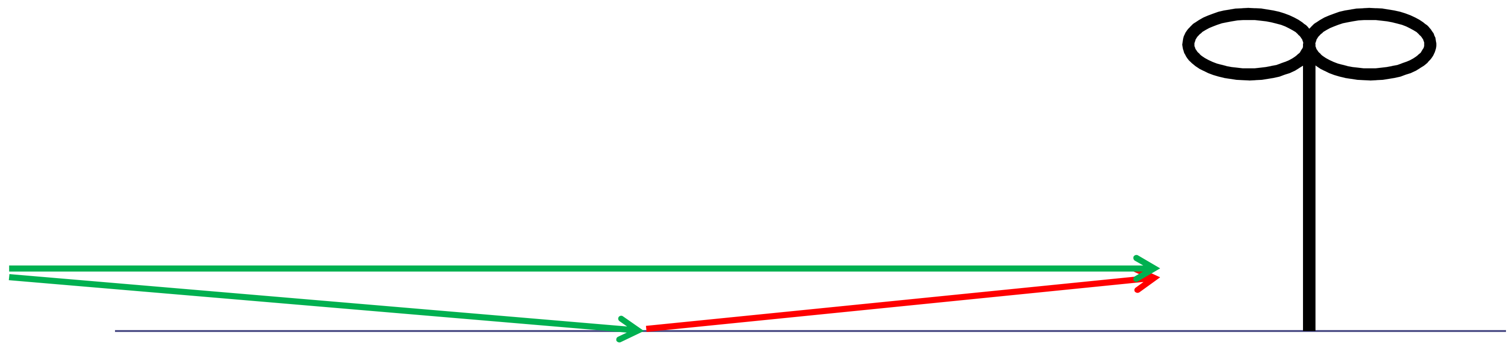



LAKE MICHIGAN
Downtown Inset
Brown Line
Green Line
Purple Line
Red Line
Blue Line
Lake St.
Wells St.
Van Buren St.
Congress Pkwy
Wabash Ave.
State St. subway
Dearborn St. subway
Washington
Quincy
LaSalle
Clark
Lake
State
Randolph
Madison
Adams
Monroe
Jackson
Library
Orange Line
use card or pass; walk between elevated & subway
See Downtown Inset
RED LINE
PURPLE LINE
continues downtown weekday rush hours
YELLOW LINE
weekdays only
BROWN LINE
BLUE LINE
GREEN LINE
ORANGE LINE
Linden
Central
Noyes
Foster
Davis
Dempster
Main
South Blvd
Howard
Jarvis
Morse
Loyola
Granville
Thorndale
Bryn Mawr
Berwyn
Argyle
Lawrence
Wilson
Sheridan
Addison
Belmont
Fullerton
Sedgwick
Clark/Division
Chicago
Grand
Skokie
Kimball
Kedzie
Francisco
Rockwell
Western
Damen
Montrose
Irving Park
Addison
Paulina
Southport
Wellington
Diversey
Armitage
North/Clybourn
Merch'dise Mart
Clinton
Ashland
California
Conservatory-Central Pk. Dr.
Pulaski
Cicero
Laramie
Central
Austin
Ridgeland
Oak Park
Harlem
O'Hare
Rosemont
Cumberland
Jefferson Park
Logan Square
Division
UIC-Halsted
Racine
Medical Center
Polk
18th
Hoyne
Kedzie-Homan
Forest Park
BLUE LINE (Forest Park Branch)
(Cermak Branch) weekdays only
Central Park
Kostner
54th/Cermak
Harrison
Roosevelt
Cermak-Chinatown
35th-Bronzeville-IIT
Indiana
43rd
47th
51st
Garfield
King Dr
inbound boarding only
East 63rd
Cottage Grove
GREEN LINE (East 63rd Branch)
GREEN LINE (Ashland Branch)
Halsted
Ashland/63rd
Sox-35th
63rd
69th
79th
87th
95th/Dan Ryan
35th/Archer
Midway
September 2003
Free connection between routes
Accessible station
Park & Ride Lot
NORTH
cta
take it..

GRAND check list

- How about a (really) GIANT array?
  - Expected performances are promising!
  - Science case is exciting!
  - Potential issues/ To do list
    - Ground reflexion?

GROUND reflexion



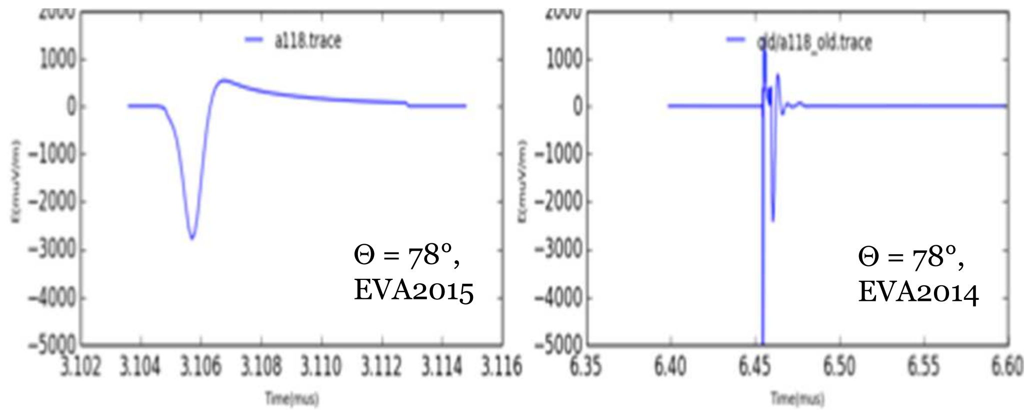
- Perfectly conducting ground: $\sigma = +\infty \Rightarrow E_{plane} = 0$ for $\theta = 90°$
- BUT:
  - Mountain slopes: wave rarely parallel to ground.
  - In reality $\sigma \neq +\infty$ (☆ full maping of $\sigma(x)$???)
  - Dedicated antenna design (large h)?

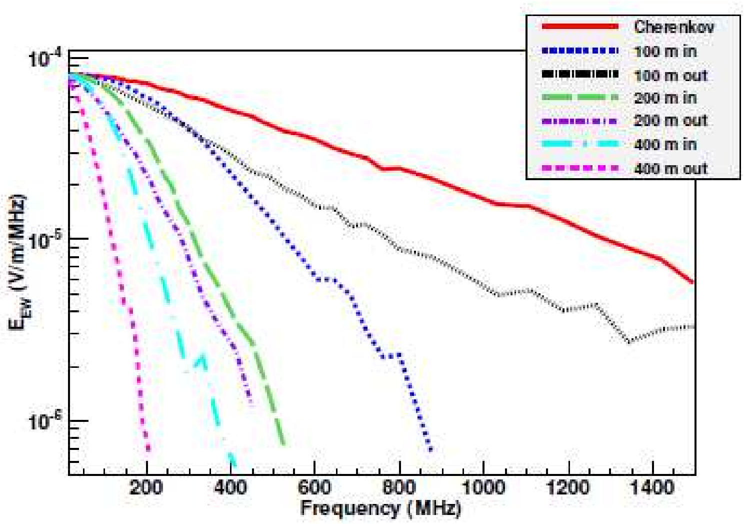
GRAND check list

- How about a (really) GIANT array?
  - Expected performances?… are promising
  - Science case?… is exciting
  - Potential issues/ To do list?
    - Ground reflexion could be an issue
    - Rigorous simulation

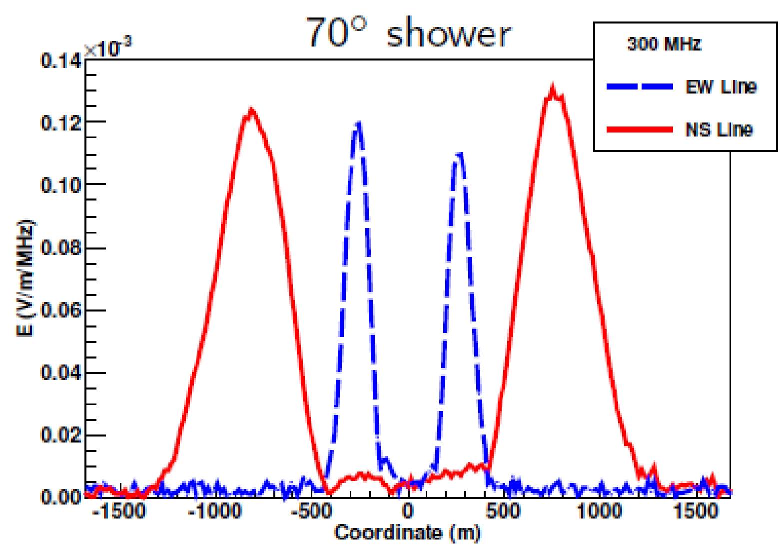
GRAND ν sensitivity study – To Do (1)

- Set-up end-to-end MC simulation code
  - Include radio simulation:
    - ZHAireS (J. Alvarez-Muniz + W. Carvalho, Santiago di Compostella)
    - EVA (K. de Vries, UV Brussels)
    - Analytical model (J. Hansen)
  - Check very inclined showers for EVA (in progress, TREND data for x-check)
  - Implement interactions with ground (reflexion & obstacles) & **antenna characteristics.**
  - Full-band simulation (Cerenkov ring)
  - **Transition radiation**



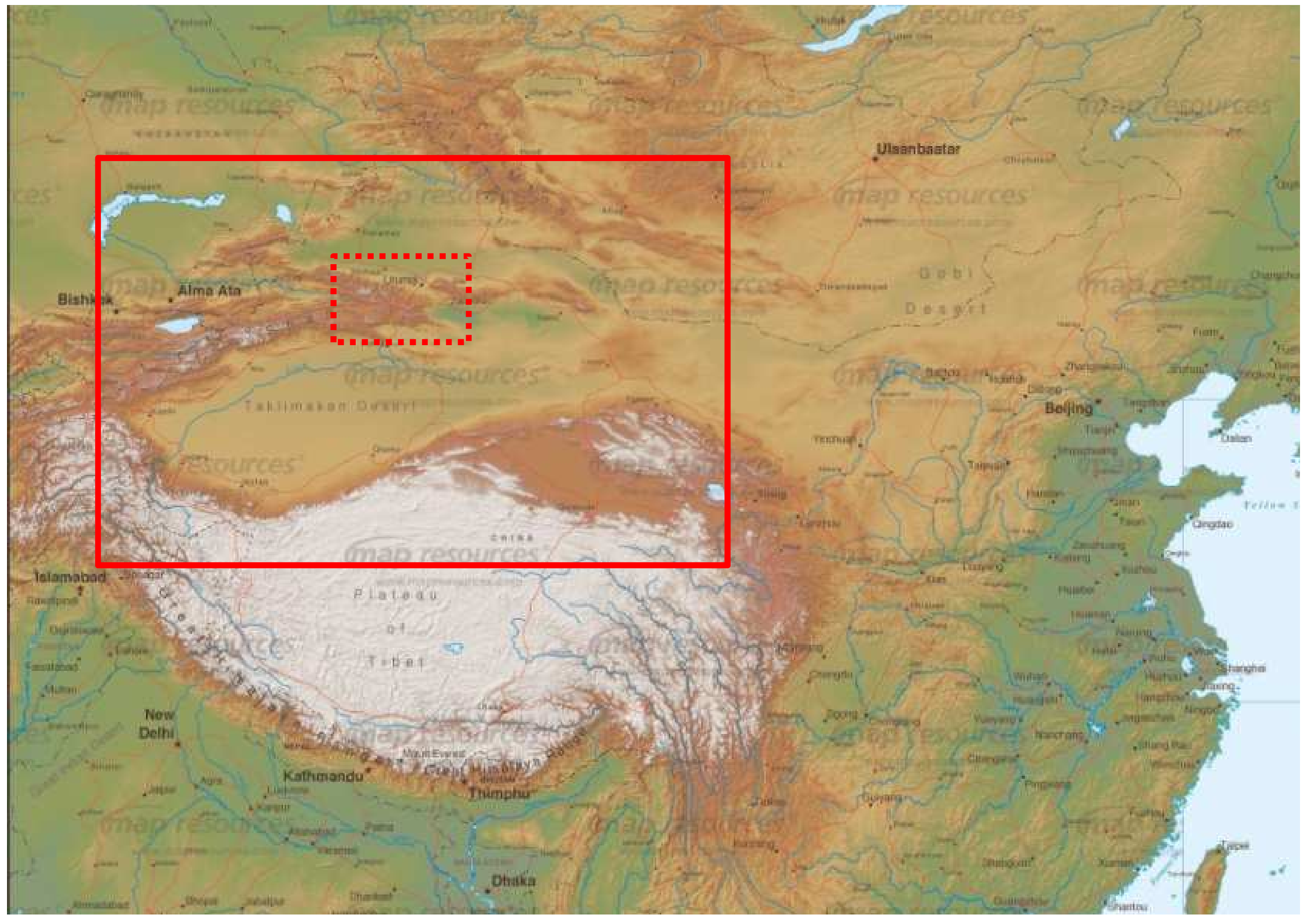


J Alvarez-Muñiz, Phys Rev D (2012)



GRAND ν sensitivity study – To Do (2)

- Giant simulation area (1'500'000 antennas over 1'000'000 km²?)
- CPU request: 1h/antenna * 100 antennas * 7 θ values * 8 φ values * 1000 core values = 8000 CPU x month

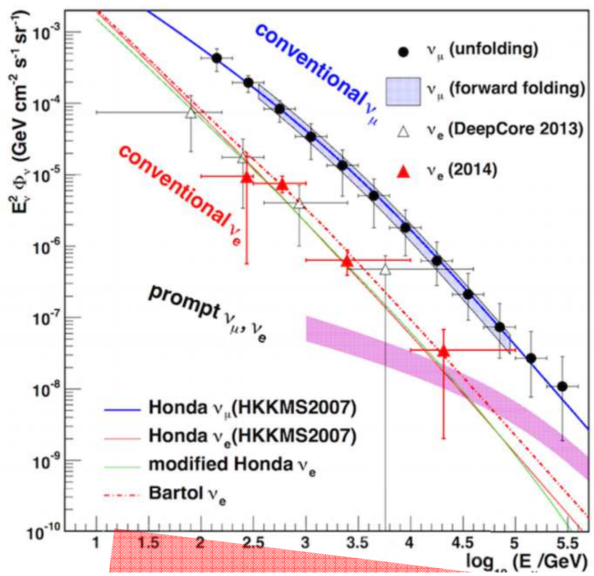


GRAND check list

- How about a (really) GIANT array?
  - Expected performances are promising!
  - Science case is exciting!
  - Potential issues/ To do list?
    - Ground reflexion could be an issue
    - Rigorous simulation: on the way
    - Background rejection?

Neutrino cosmic background

Sensitivity limit for 0 candidates within 3 years…
=> Background rejection is a major challenge.



- «Cosmic» background sources:
  - Atmospheric ν and μ fluxes negligeable beyond 10^{16}eV.
  - UHECRs wrongly reconstructed below the horizon
    - «Old» showers
      ⇨ larger X_{max}
      ⇨ larger footprint at ground
    - Cut on reconstructed zenith angle θ> horizon - 1° kills large fraction of background thanks to angular resolution.

Terrestrial background

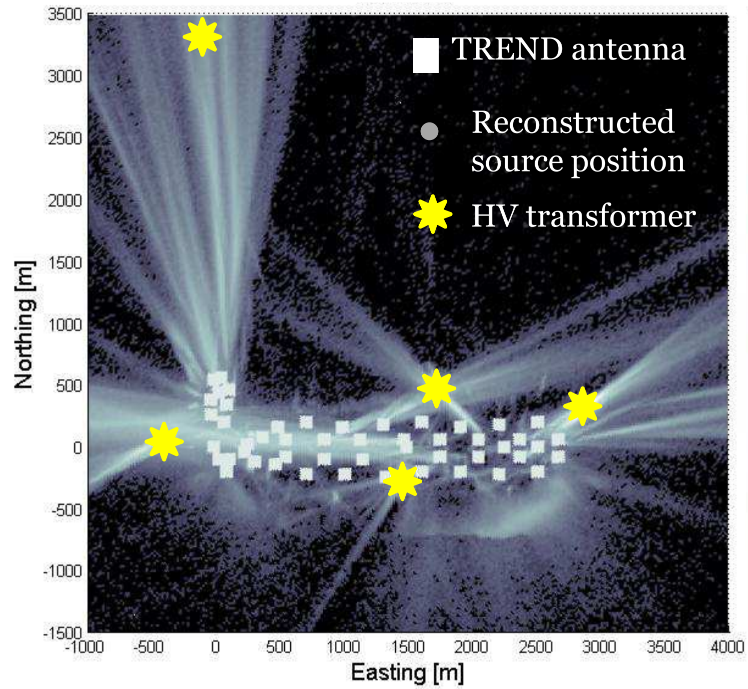
- GRAND bckgd event rate estimation:

TREND50:
~30kEvents/day/km²
(~1.5 10^7 coincs in 317 DAQ days)

TREND50 → GRAND:
Area x40000 but antenna density /25
⇨ Trig density /2000 (safe estimate)
Large step size helps kill background!

GRAND:
<15 events/day/km²
(safe estimate)
3 10^8 evts/year over full array

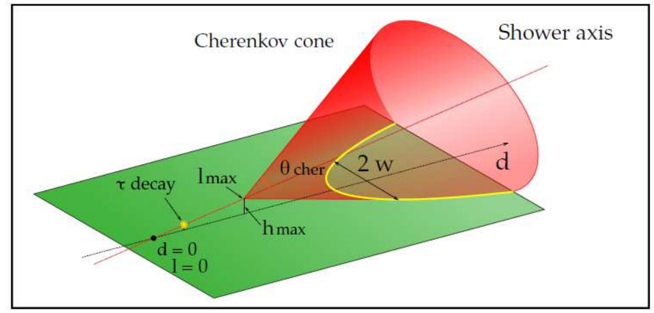
TREND 2011-2012 data



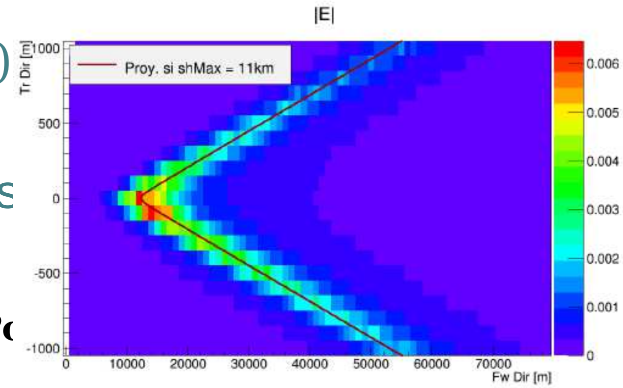
Lesson learnt from TREND: even in remote sites, many background transient signals of various origin (HV, trains, planes, thuderstorms, etc.)

Expected ν event rate:
0-100 events/year

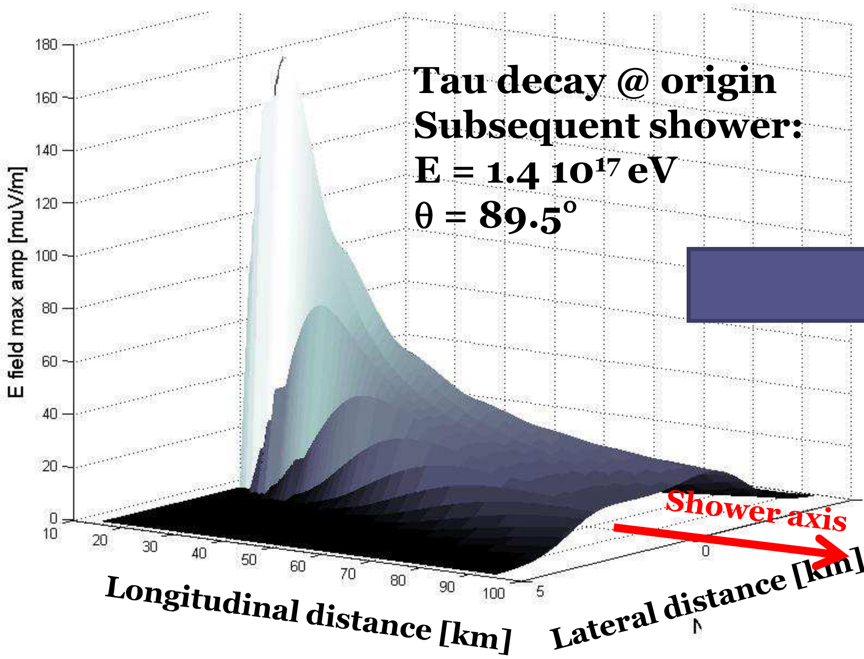
Terrestrial background rejection

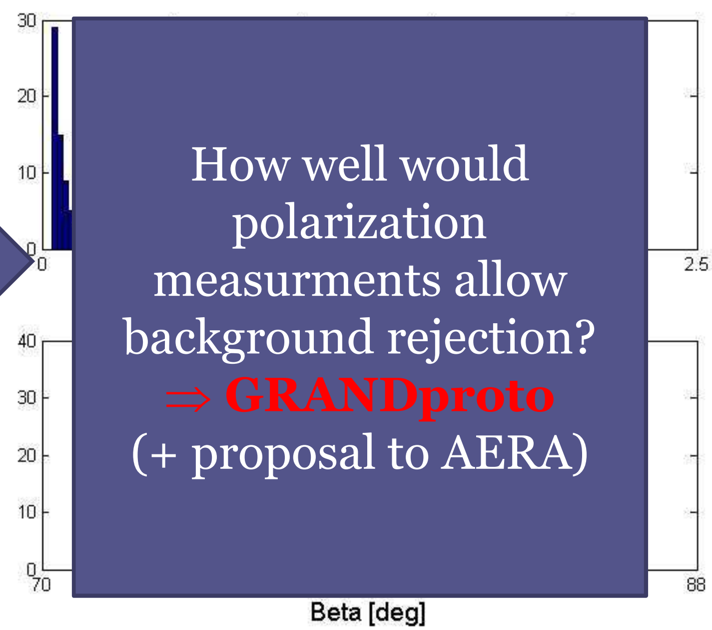


- EAS signatures
  - Trigger pattern at ground
    (beamed emission with flat wavefront & lateral drop)
  - Cerenkov cone
  - Polarization : $\perp B_{geo}$ & $\perp v$ at 1st order on all antennas



30-80MHz Efield computation
ZHAireS simulation code





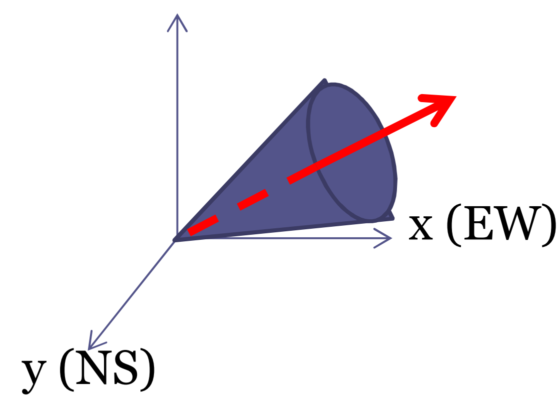
How well would polarization measurments allow background rejection?
⇒ **GRANDproto**
(+ proposal to AERA)

Polarization measurment

- Assume that for every wave detected, the polarisation expected under EAS hypothesis can be computed within 15° for every trigged antenna.

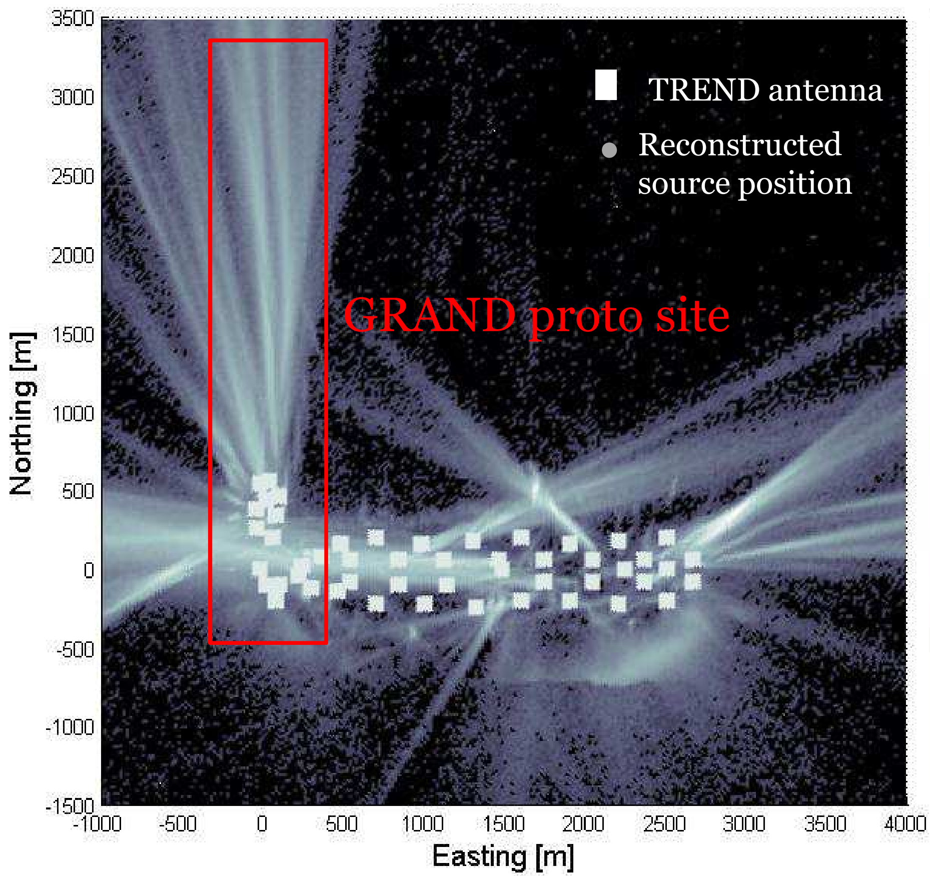
- Then probability that a wave with random polar has an « EAS-compatible » polar is $p = 0.02$… For 5-antennas: $p = 0.02^5 = 1.4\ 10^{-9}$.

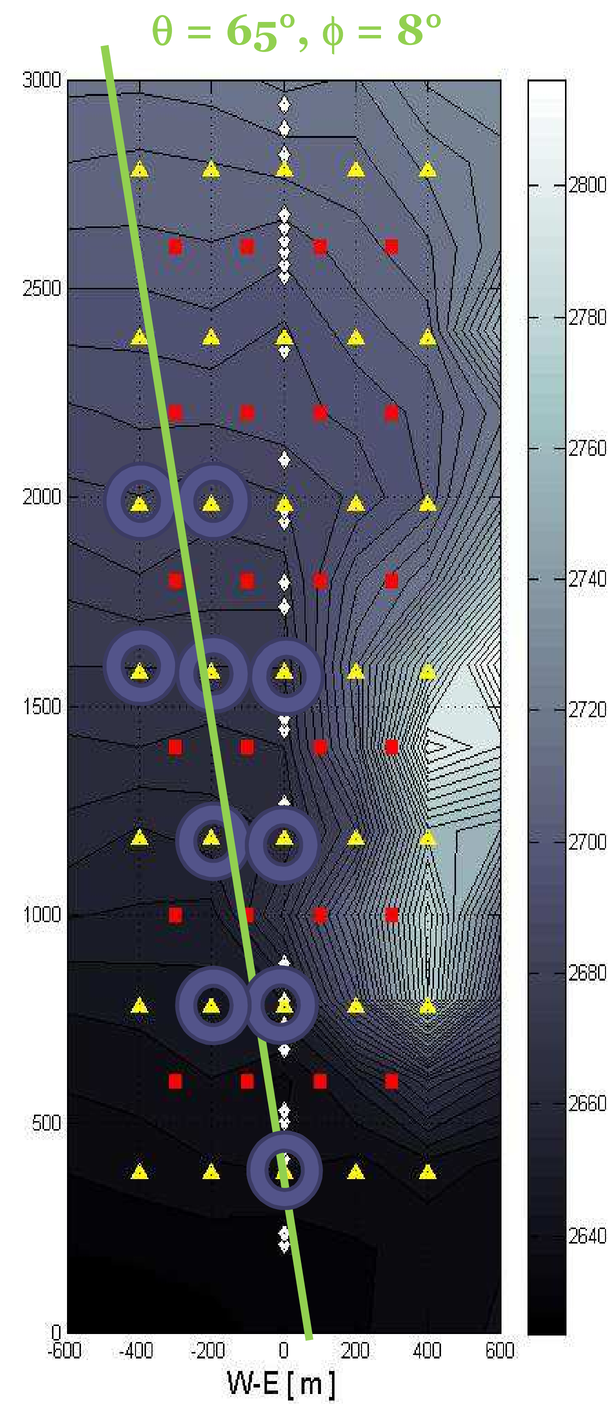
… Promising!



GRAND-proto

- **Hybrid setup composed of 35 3-polar antennas + 21(+3) scintilator array**
- Deployed at the noisiest location of TREND array, aiming at showers coming from North.

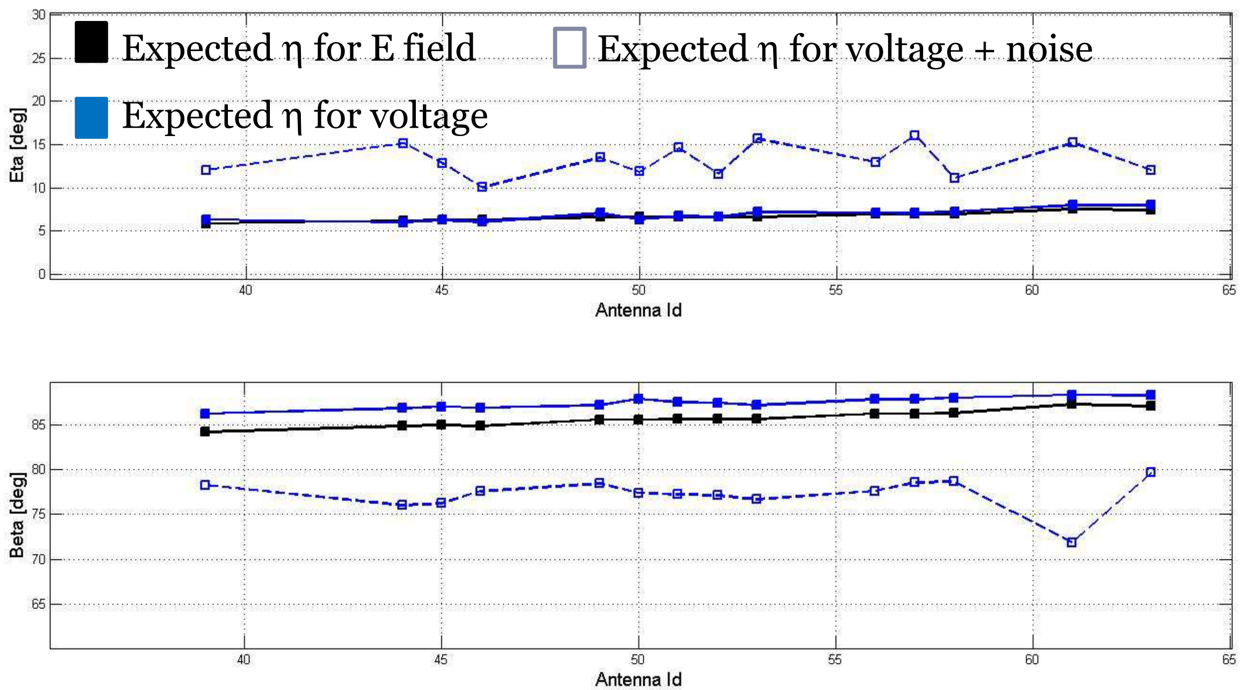


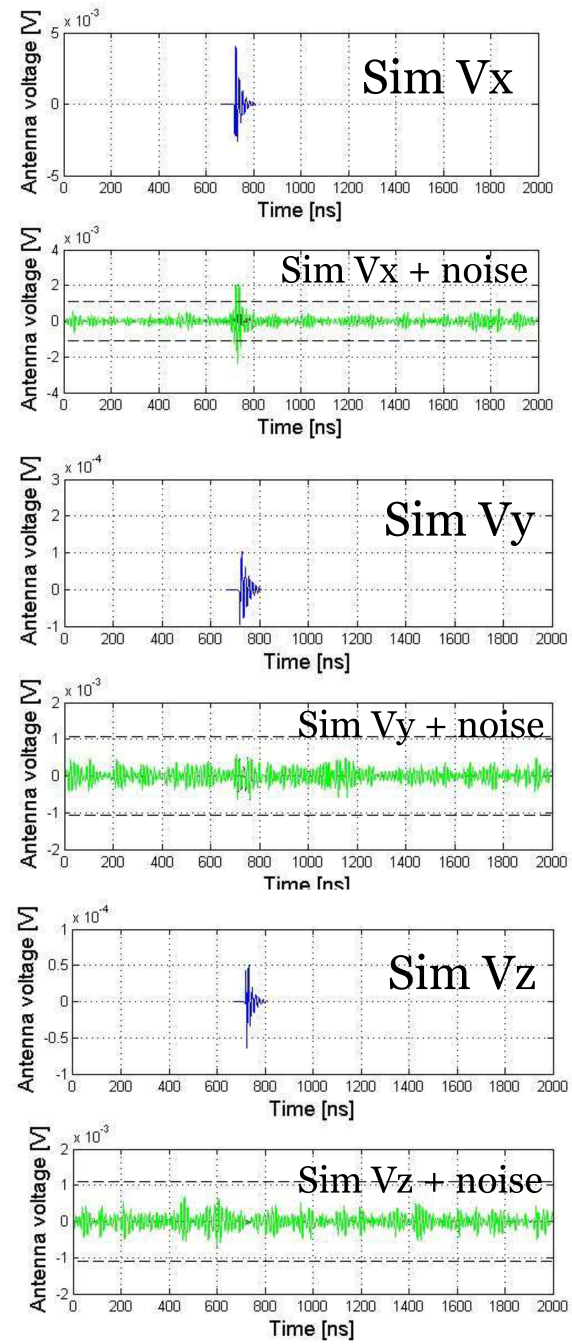


Principle of EAS polarization measurment in GRAND-proto

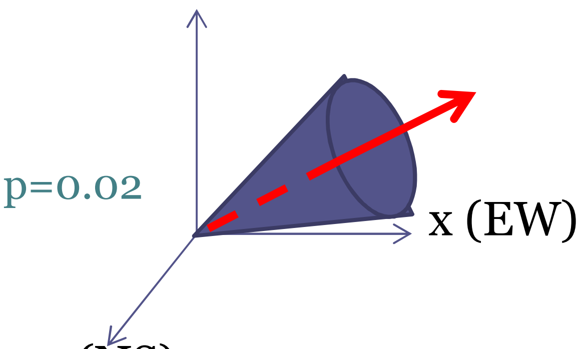
- For all trig'd antennas, compute expected η and β from simulated voltage, assuming signal due to EAS.
- If experimental values matches computed ones: **EAS tag**
- Off-line validation of EAS candidates with **scintillator array** **(requires known efficiency for scintillator array)**

⇨ **Quantitative** evaluation of EAS identification





Principle of EAS polarization measurment in GRAND-proto



- How good do we have to be? A very rough estimate.

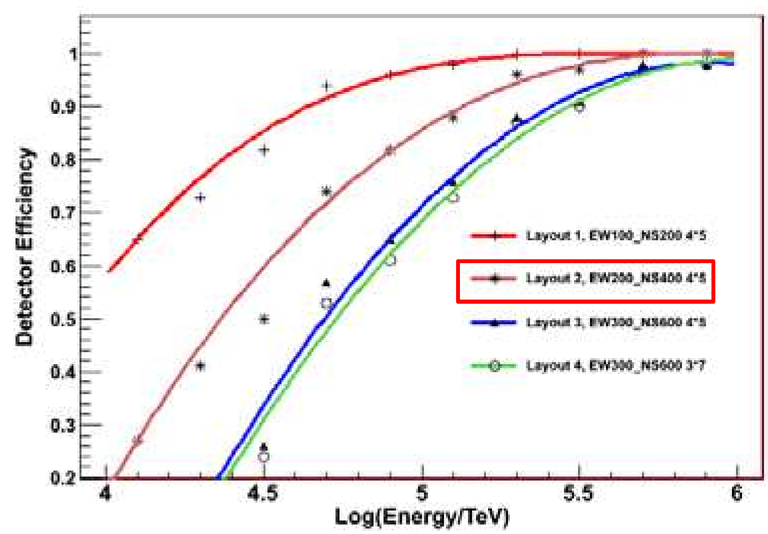
  If we allow 15° tolerance on reconstructed polarisation angle:
  - Random polar may be tagged as valid for one antenna with p=0.02
  - **$p=0.02^5 = 1.4\ 10^{-9}$ for 5-antennas events**

    ($7\ 10^{-15}$ for 8-antennas events)

- How GRANDproto can be instrumental for GRAND ?

  - Valid dataset ⇔ event for which EAS nature can be cross checked
    - Events from below horizon / known bckgrd sources (check bckgrd rejection)
    - Events with (E,θ,φ) for which ε_{scint} >90% (check signal validation)
  - Expected event rate?
    - Background: 50Hz event rate ⇨ 1 year live to reach total stat of $1.5\ 10^9$ events.
    - Signal: ~0.5 event/day with $E>2\ 10^{17}$eV for 45<θ<70° & φ in ±20° around North.

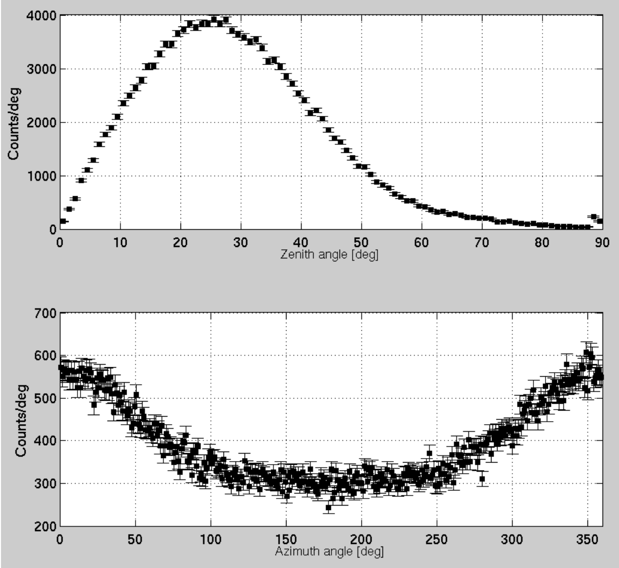
Q. Gou et al., GRANDproto, ICRC proceedings

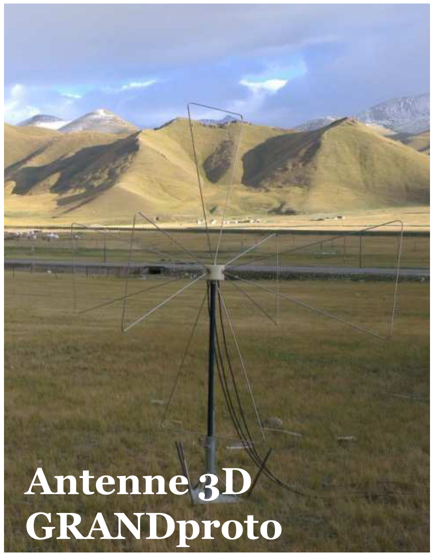


GRANDproto status

- Array fully funded by NAOC & IHEP.
- 6 antennas & 6 scintillators deployed in summer 2015 to test hardware, DAQ and recons. To be completed in summer 2016.
- Radio array electronics developped @ LPNHE. Now under test, to be validated on site March 2016.
- Data taking ⇨ 2019.

Reconstructed scint events



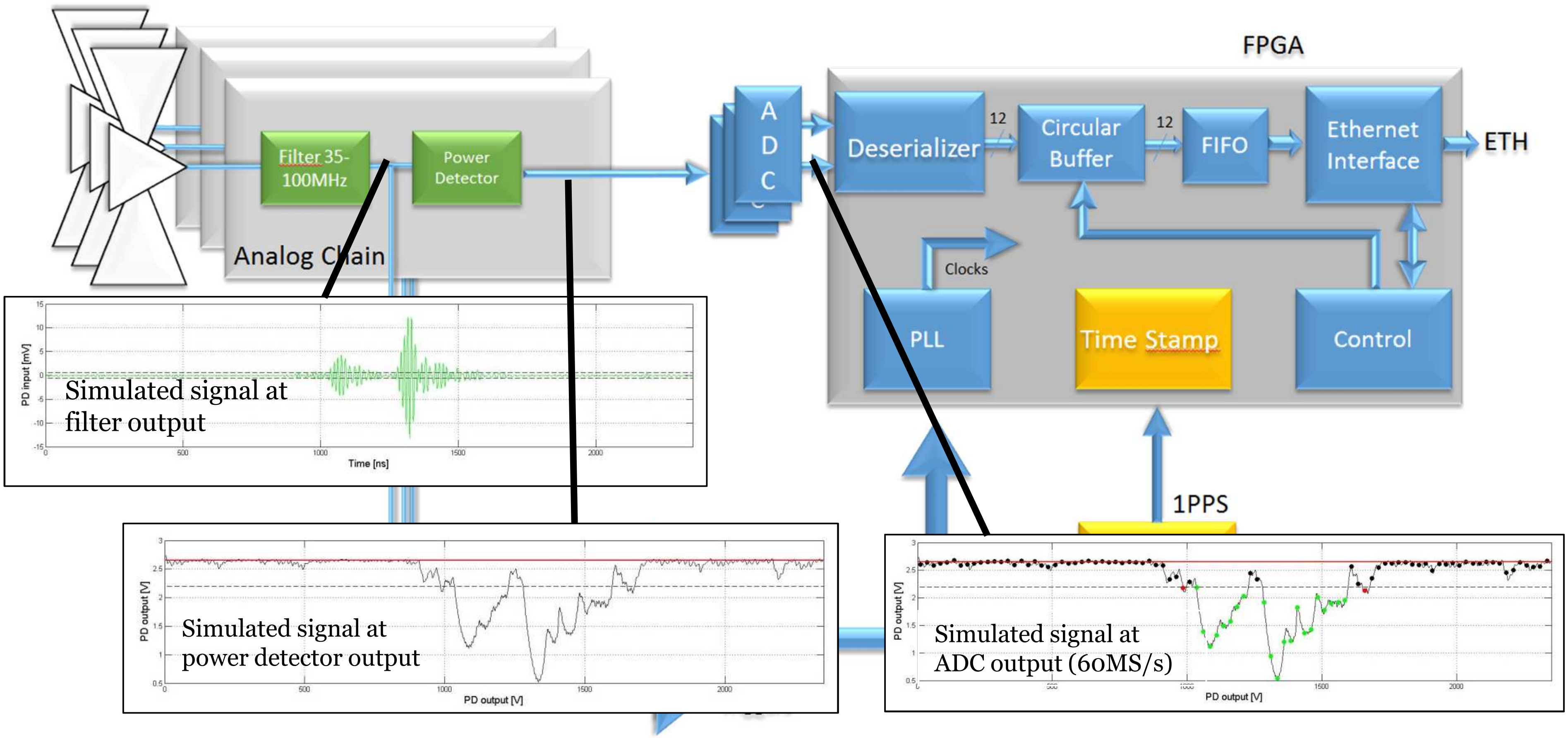


GRAND check list

- How about a (really) GIANT array?
  - Expected performances are promising!
  - Science case is exciting!
  - Potential issues/ To do list?
    - Ground reflexion could be an issue
    - Rigorous simulation: on the way
    - Background rejection: GRANDproto
    - Technological challenges?

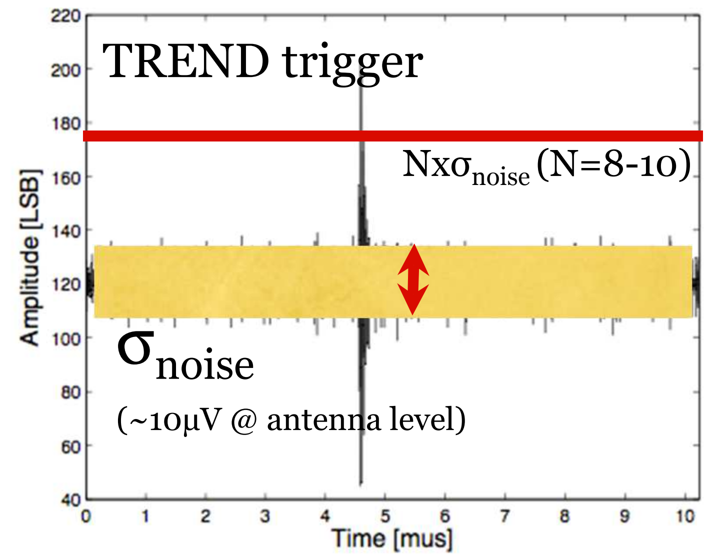
GRAND FE electronics

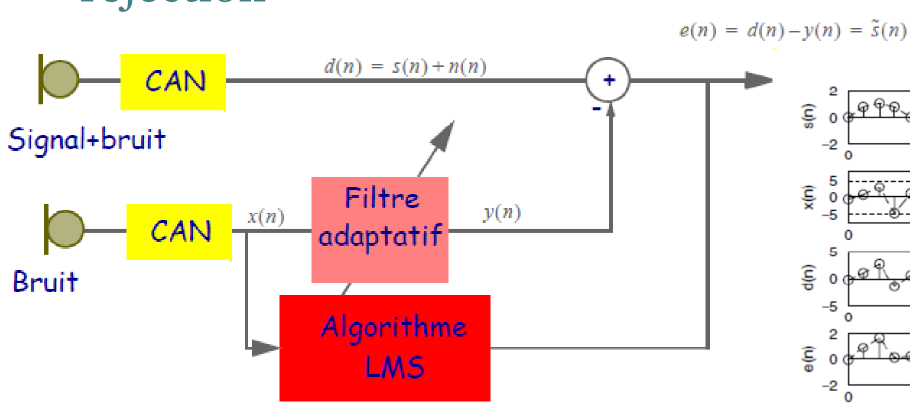
- GRANDproto electronics as base for developements for GRAND detection unit:
  - Pre-trigger on (filtered) antenna signal
  - Enveloppe detection by power detector
  - « Slow » sampling (100 -> 60MS/s)



GRAND trigger

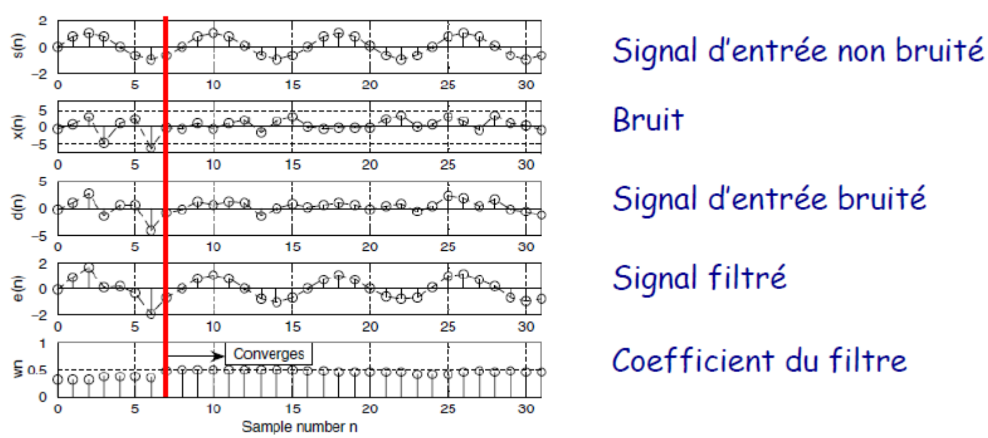
- Enhanced signal processing @ FPGA level:
  - Very little done on the topic so far… Could be improved because we KNOW expected signal (simulations) AND background (data).
  - Adaptative filter
  - Signal correlation
  - ⇒ 2^{nd} level trigger @ FPGA level
  - ⇒ better threshold, better background rejection





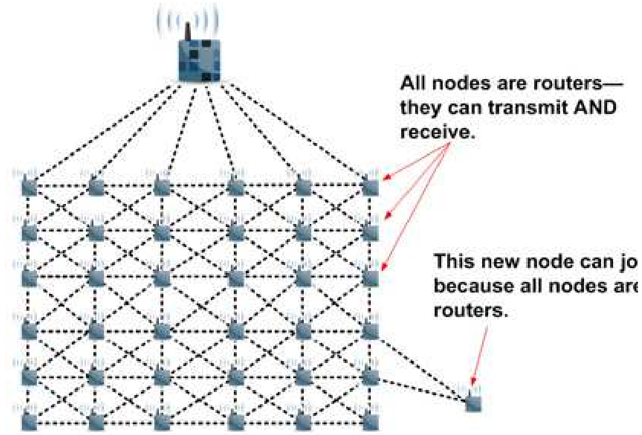
$y(n) = w_n x(n)$

$w_{n+1} = w_n + 0,01 e(n) x(n)$

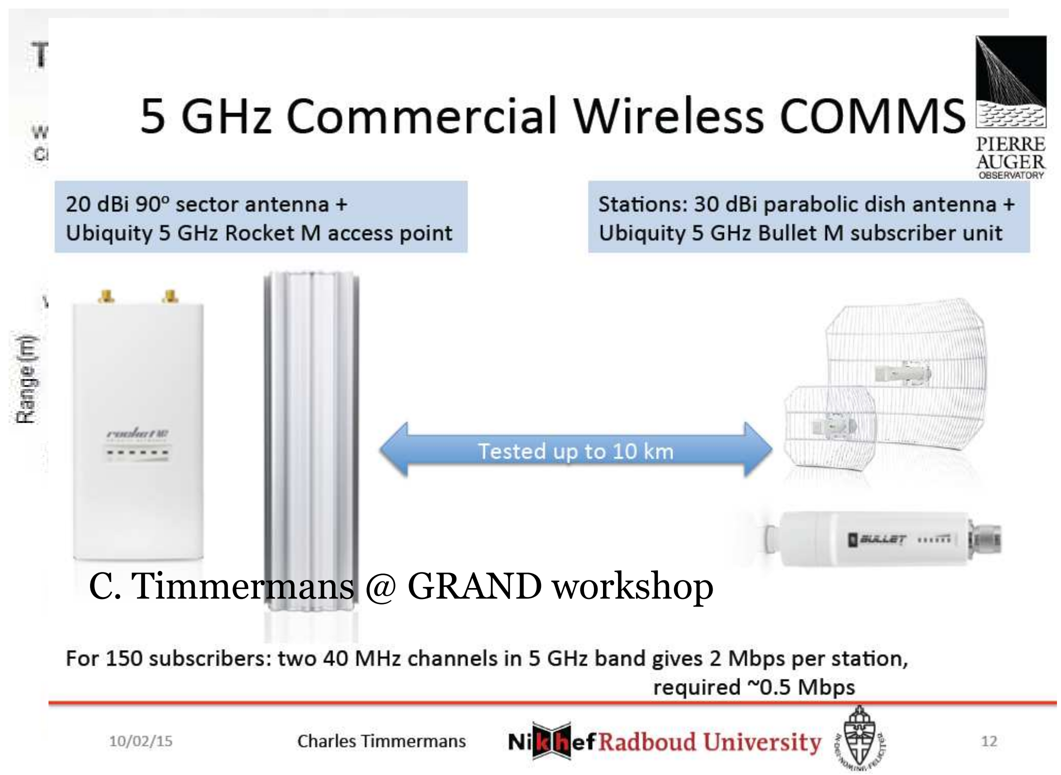


GRAND data format & transfer

- Save minimal info: 5x16 = 80 bits per trigger
  - Trig time (2x16bits <-> 4s)
  - Amplitude (16 bits
  - Polarization info (2 angles: 2x8 bits)
  - Others (ID, monitoring…)
- Assuming <u>trig rate = 10Hz</u> (☆ safe estimate?)
- 800bits/antenna/s ⇨ **20MBy/s** data rate for full array
- Solution for data transfer? Many development in recent years for commercial applications may be useball/usefull.
  - Smart Mesh + Wireless HART
  - Wifi (802.11xx), WiMax
  - GSM
  - …



~10$/unit



C. Timmermans @ GRAND workshop

The GRAND array: 200k antennas over 200’000km^2?

Huge technological challenge, but not unrealistic:

- Radio-antennas as simple, robust & stable detectors.
- Keep it as basic as possible.
- Rely on industrial and validated technologies (GPS, data transfer).
- Engineering array (~1000 antennas) to validate concept & technology (CR physics)
- Lots of R&D ahead.

- Caution: science case directly impacts technical aspects.

Neutrinos → UHECRs → FRBs, EoR

Neutrinos
Antenna max amplitude & trig time
Limited antenna aperture

UHECRs
+ Waveform?
+ Frequency spectrum?
+ Large antenna aperture

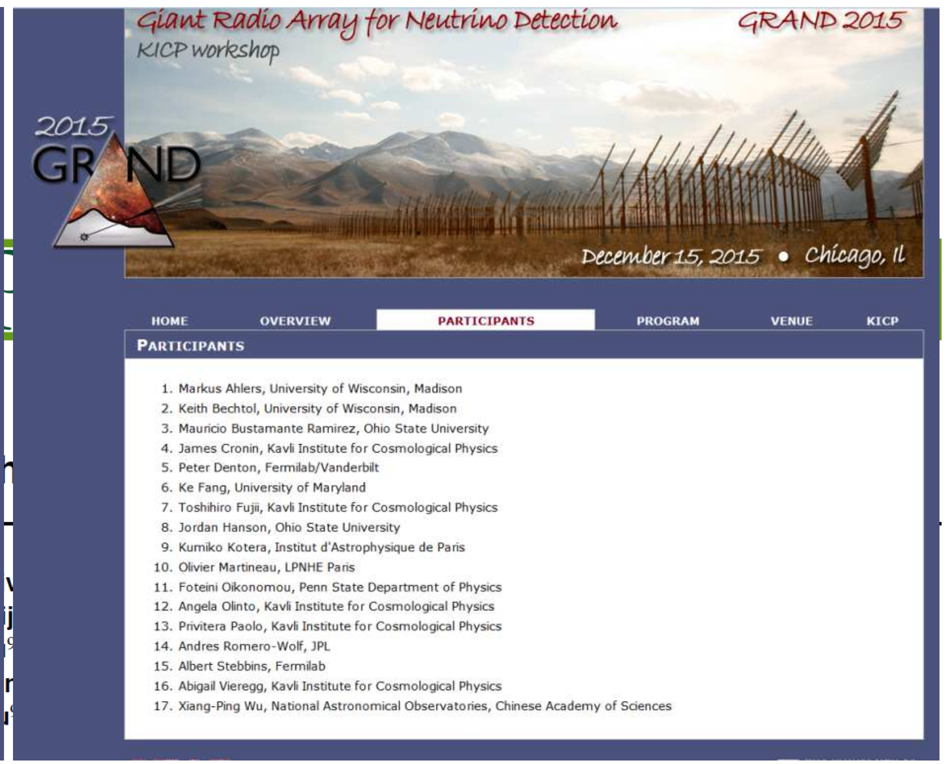
FRBs, EoR
+ ~ms-long waveforms
+ Higher frequencies

GRAND check list

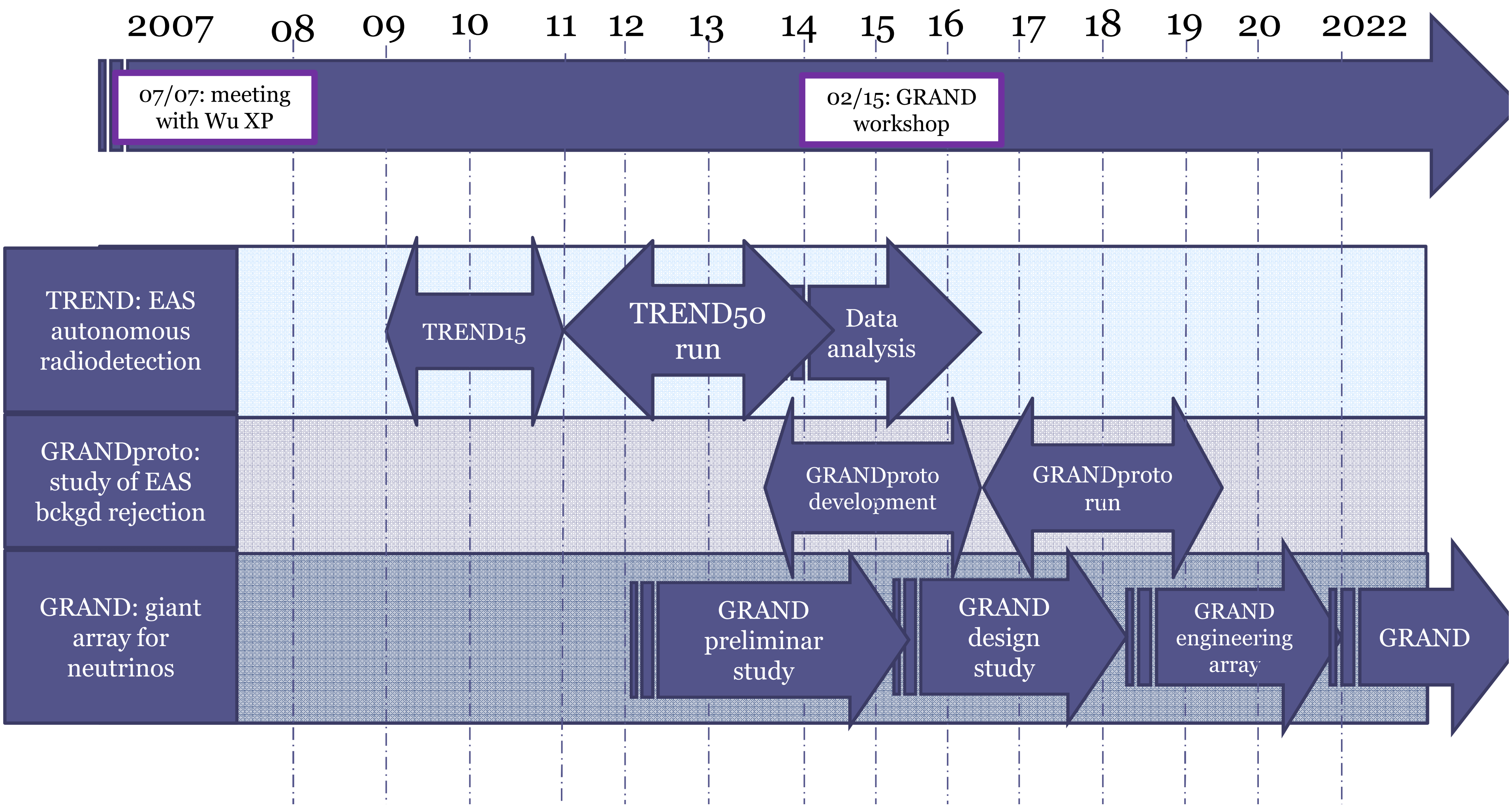
- How about a (really) GIANT array?
  - Expected performances are promising!
  - Science case is exciting!
  - Potential issues/ To do list?
    - Ground reflexion could be an issue
    - Rigorous simulation: on the way
    - Background rejection: GRANDproto
    - Technological challenges: leads to explore

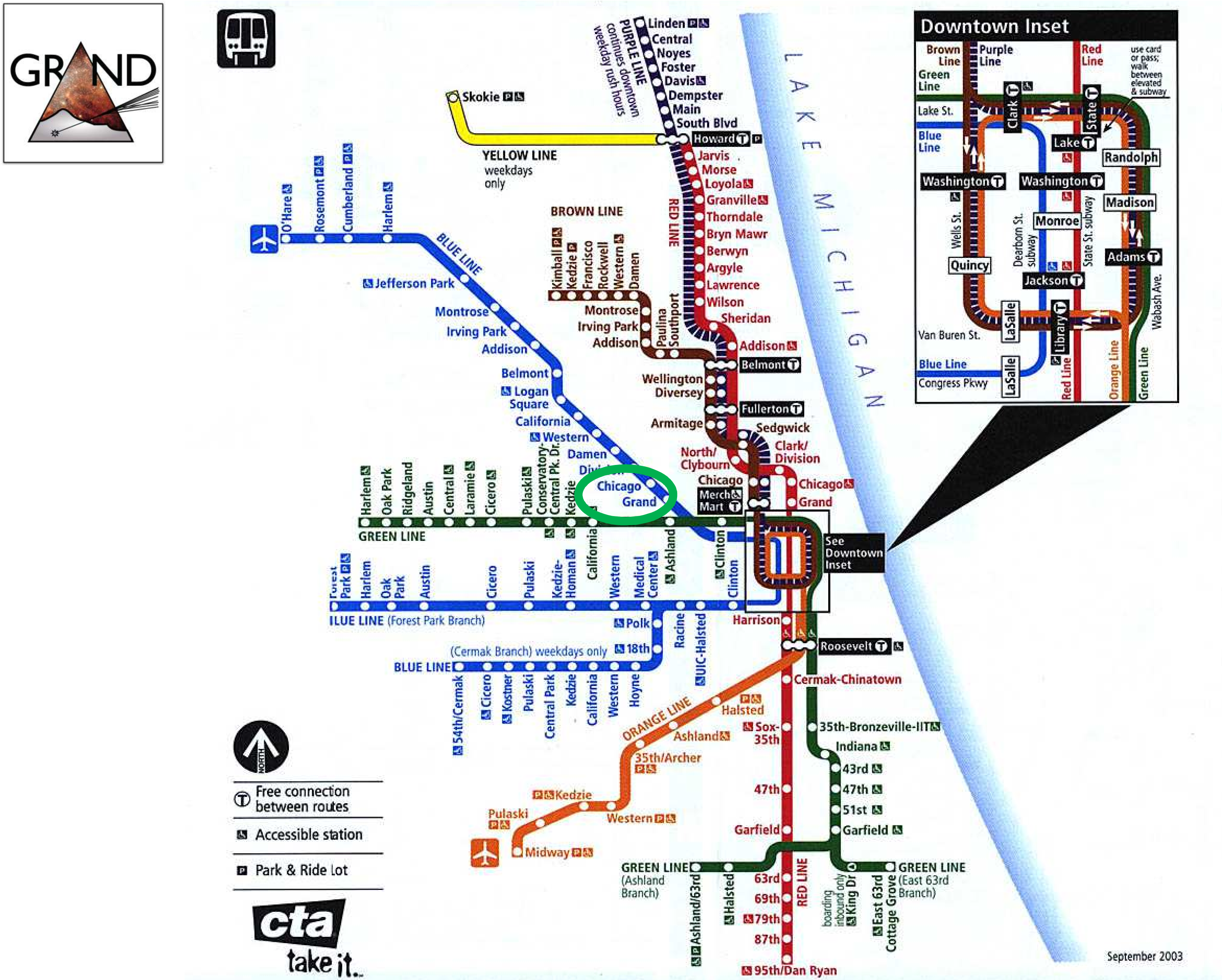
GRAND people

- GRAND study initiated (2012-2014) with very limited ressources (OM+ V. Niess for ν sensitivity study, K. Kotera for science case)
- Seminal ILP workshop @ LPNHE (Feb. 09-11, 2015)
  - 38 participants (AUGER, IceCube, ANITA, ARA, …)
  - Define GRAND strategy: ambitious VHE neutrino astronomy + post-AUGER program
  - Interest raised, individuals getting involved.
- Work getting organised!



(Tentative) timeline





Downtown Inset
Brown Line
Purple Line
Green Line
Red Line
use card or pass; walk between elevated & subway
Lake St.
Blue Line
Clark
State
Lake
Randolph
Washington
Washington
Madison
Wells St.
Dearborn St. subway
Monroe
State St. subway
Quincy
Jackson
Adams
Wabash Ave.
Van Buren St.
LaSalle
Library
LaSalle
Blue Line
Congress Pkwy
Red Line
Orange Line
Green Line
LAKE MICHIGAN
See Downtown Inset
Linden
Central
Noyes
Foster
Davis
Dempster
Main
South Blvd
Howard
PURPLE LINE continues downtown weekday rush hours
Skokie
YELLOW LINE weekdays only
Jarvis
Morse
Loyola
Granville
Thorndale
Bryn Mawr
Berwyn
Argyle
Lawrence
Wilson
Sheridan
Addison
Belmont
Fullerton
Sedgwick
Clark/ Division
Chicago
Grand
RED LINE
BROWN LINE
Kimball
Kedzie
Francisco
Rockwell
Western
Damen
Montrose
Irving Park
Addison
Paulina
Southport
Wellington
Diversey
Armitage
North/ Clybourn
Chicago
Merch& Mart
O'Hare
Rosemont
Cumberland
Harlem
BLUE LINE
Jefferson Park
Montrose
Irving Park
Addison
Belmont
Logan Square
California
Western
Damen
Chicago
Grand
Harlem
Oak Park
Ridgeland
Austin
Central
Laramie
Cicero
Pulaski
Conservatory-Central Pk. Dr.
Kedzie
California
Ashland
Clinton
GREEN LINE
Forest Park
Harlem
Oak Park
Austin
Cicero
Pulaski
Kedzie-Homan
Western
Medical Center
Clinton
BLUE LINE (Forest Park Branch)
Polk
18th
Racine
UIC-Halsted
(Cermak Branch) weekdays only
BLUE LINE
54th/Cermak
Cicero
Kostner
Pulaski
Central Park
Kedzie
California
Western
Hoyne
Harrison
Roosevelt
Cermak-Chinatown
ORANGE LINE
Halsted
Ashland
35th/Archer
Kedzie
Pulaski
Western
Midway
Sox-35th
47th
Garfield
35th-Bronzeville-IIT
Indiana
43rd
47th
51st
Garfield
GREEN LINE (Ashland Branch)
Ashland/63rd
Halsted
63rd
69th
79th
87th
95th/Dan Ryan
RED LINE
boarding inbound only
King Dr
East 63rd
Cottage Grove
GREEN LINE (East 63rd Branch)
NORTH
Free connection between routes
Accessible station
Park & Ride Lot
cta take it.
September 2003

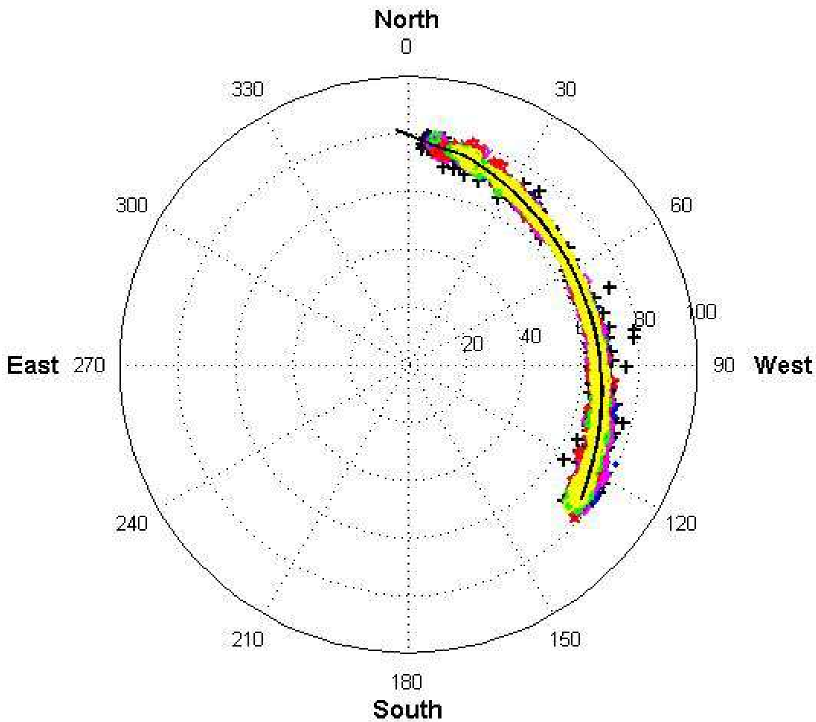
Backup

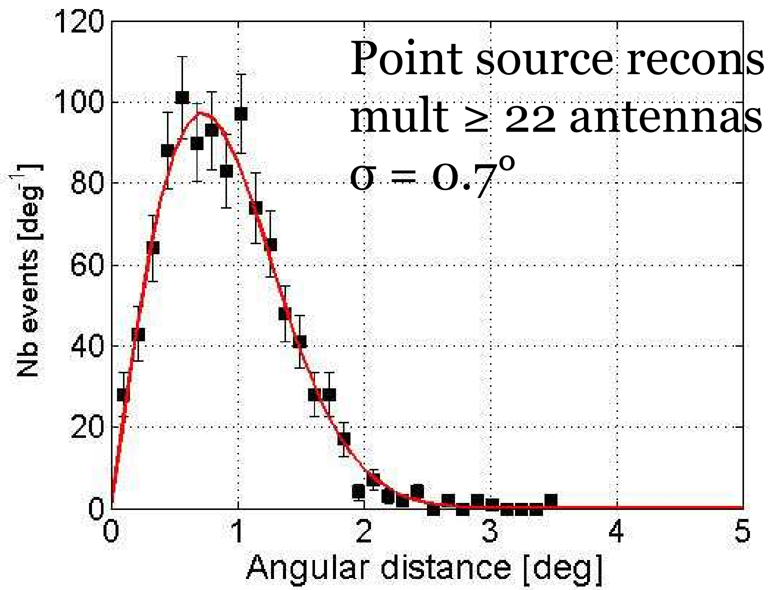
TREND

RADIO PERFORMANCES: DIRECTION RECONSTRUCTION

- **Plane track**

- 3037 events in 4 minutes
- $\Theta > 60°$
- Max multiplicity: 40

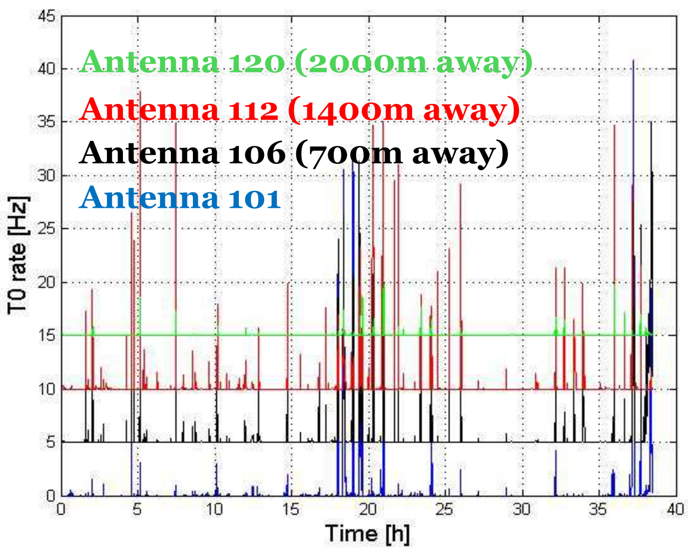




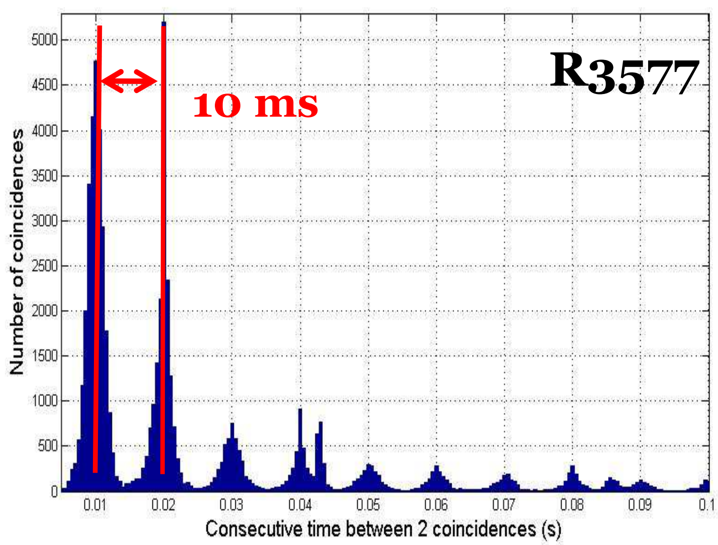
Total angular resolution <1.5° on the track
(and improves with smaller zenithal angle)

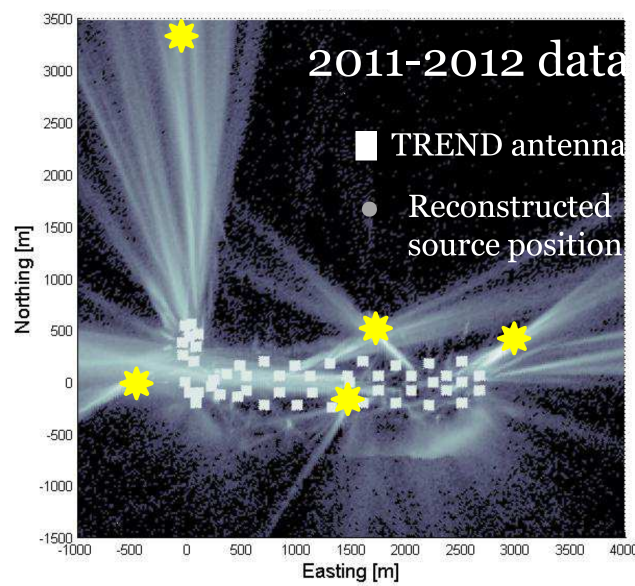
Estimated antenna trigger timing error: ±10ns

TREND trigger performances



- T0 rate <100Hz for 90% of the time on all antennas.
- **DAQ efficiency ~ 70%.**
- Large trigger rate variations at all time scales on all antennas: **«noise bursts»**
- **Noise is correlated between antennas: common (physical) origin.**
- Time delay between consecutive events & point reconstruction points dominantly towards **HV sources.**





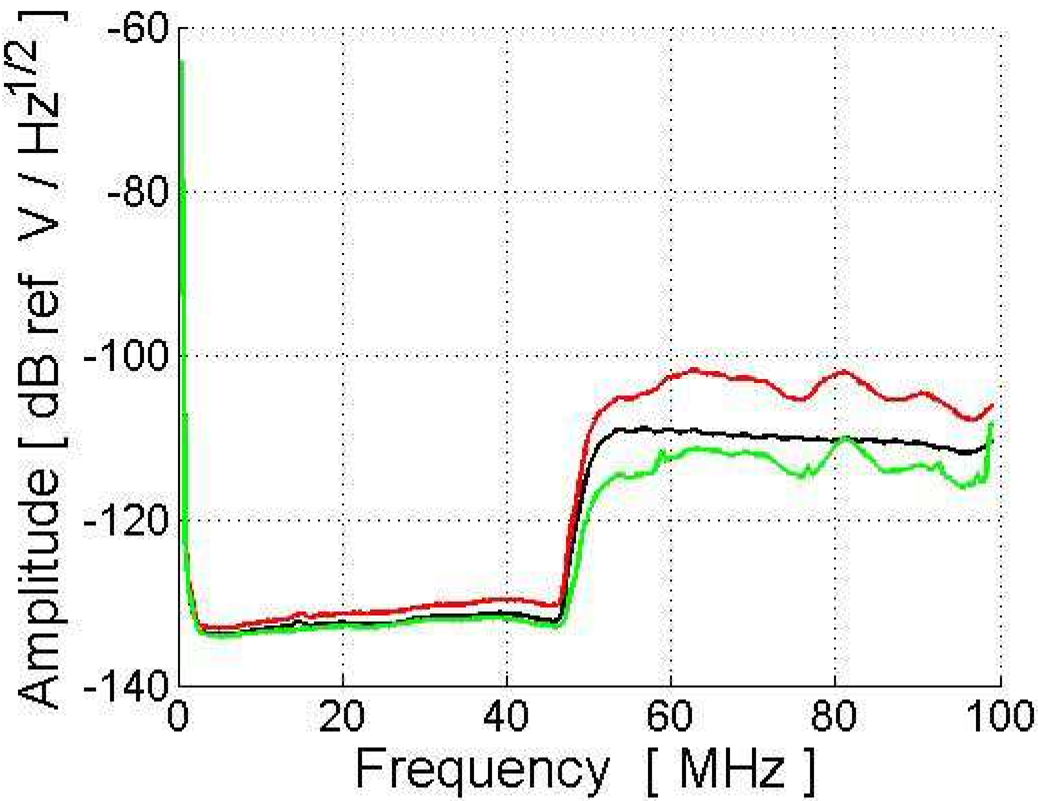
<u>2011-2012 data:</u>
317 DAQ days analyzed

$3.7\ 10^9$ triggers recorded
$2.4\ 10^8$ coincidences
<u>~10Hz</u> average coinc rate over whole array

Absolute calibration (under development)

Use load measurement

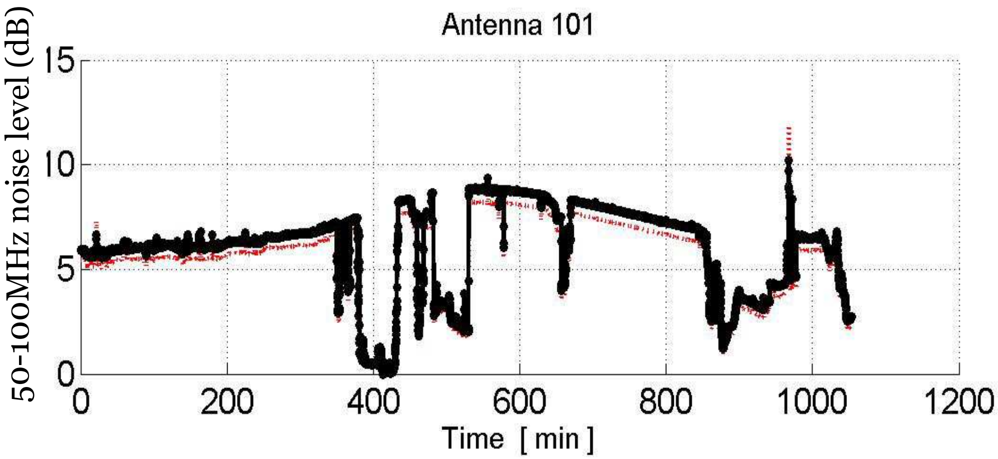
- PSD_{load}: power spectum density with input = 75Ω load.
- PSD_{ref} with input = antenna right after load.
- $PSD_{current}$ with input = antenna at time *t*.

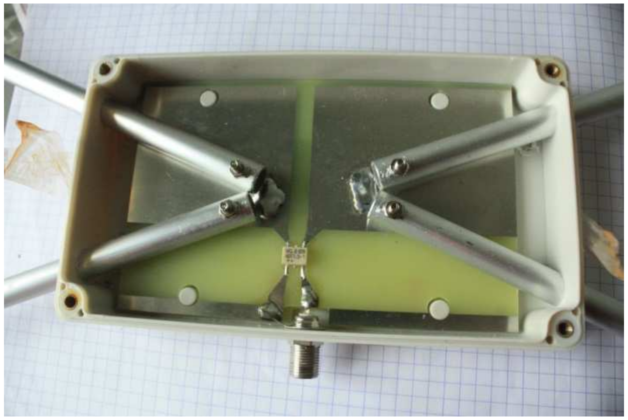


$$G_{dB}(t) = PSD_{load} + PSD_{current}(t) - PSD_{ref}$$

TREND issues

- «You get what you pay for»: **system reliability** questionnable
  - Sudden drops in gain **[not solved]**
  - Aging (antennas, amplifiers, optical system, computers…)

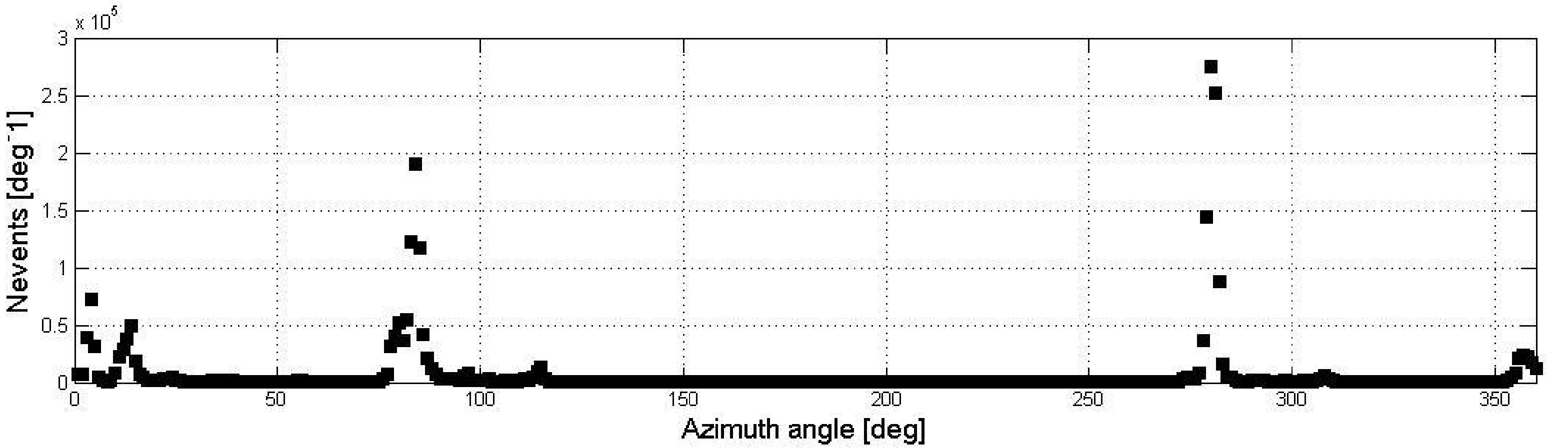




- Significant maintenance effort required
- Reduced detection efficiency
- Monitoring of efficiency & absolute calibration (very) challenging

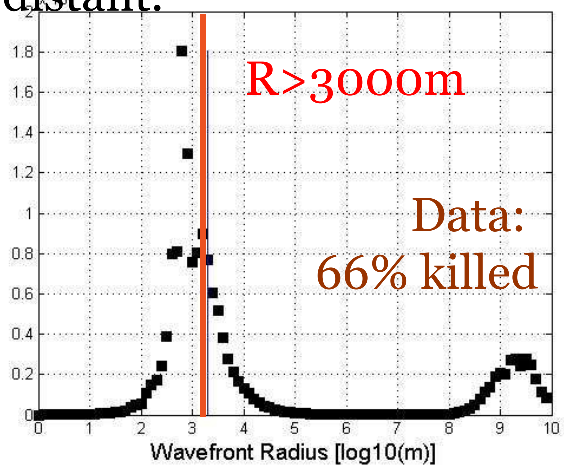
TREND

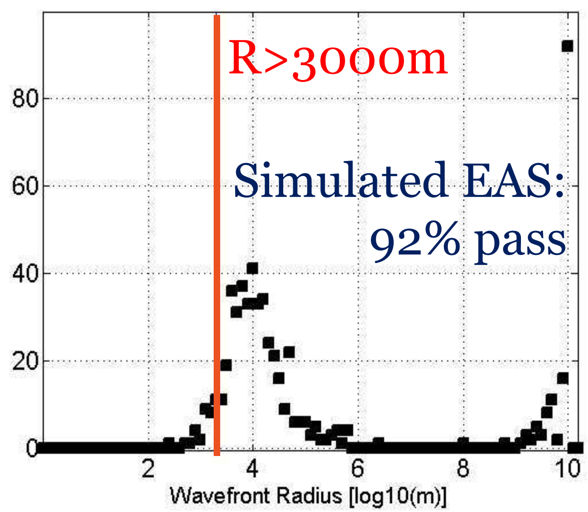
- Azimuth distribution (2011-2012 data)



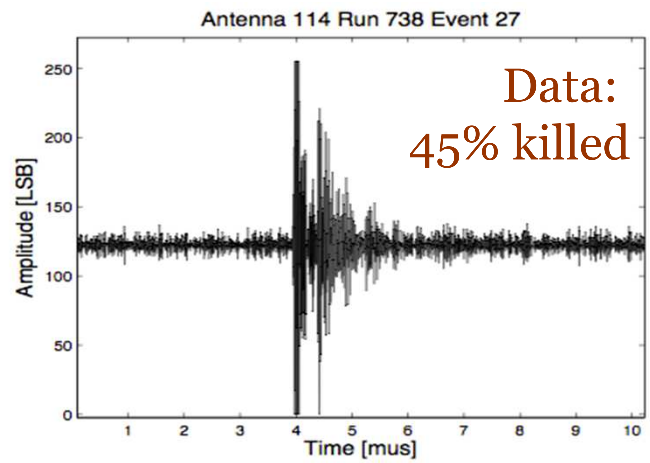
Discriminating parameters

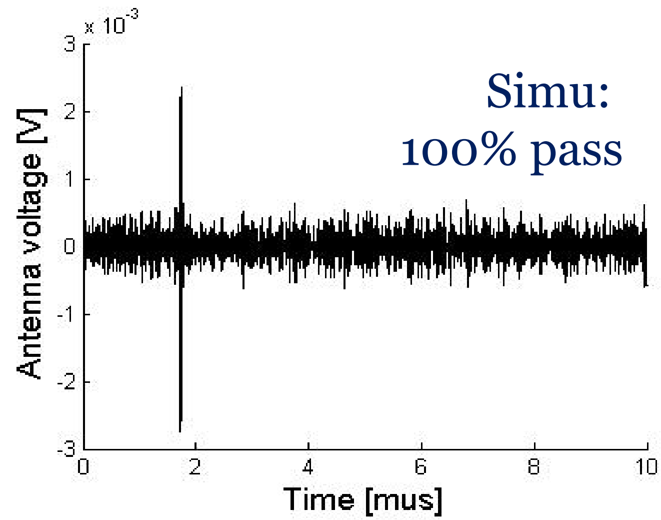
- Spherical wave recons: point source reconstruction of backgrd sources close to array, EAS more distant.





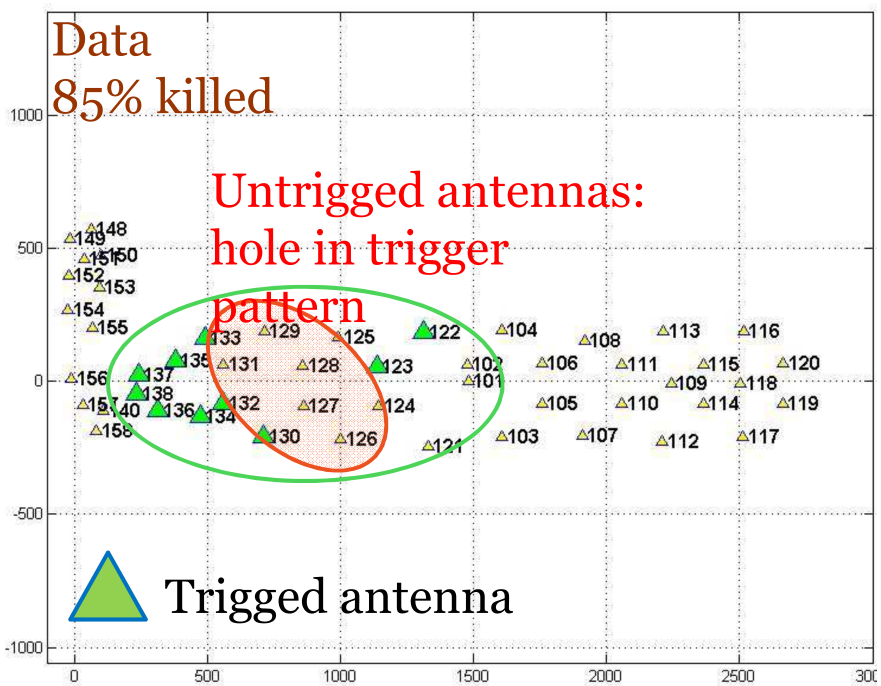
- Signal shape: prompt signal for EAS

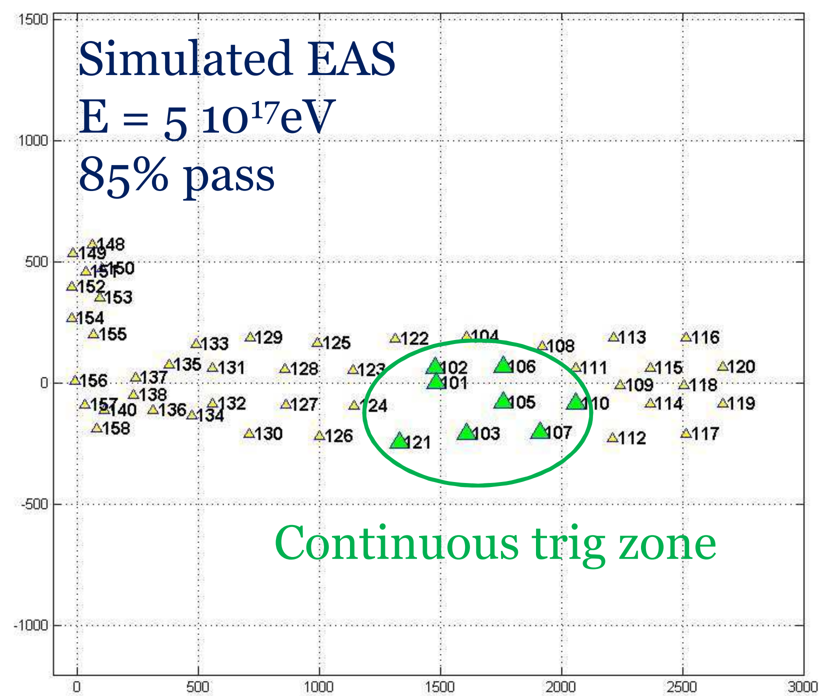




Discriminating parameters

- Array trigger pattern should be continuous for EAS (E-field linear polarization at 1st order, random for bckgd)

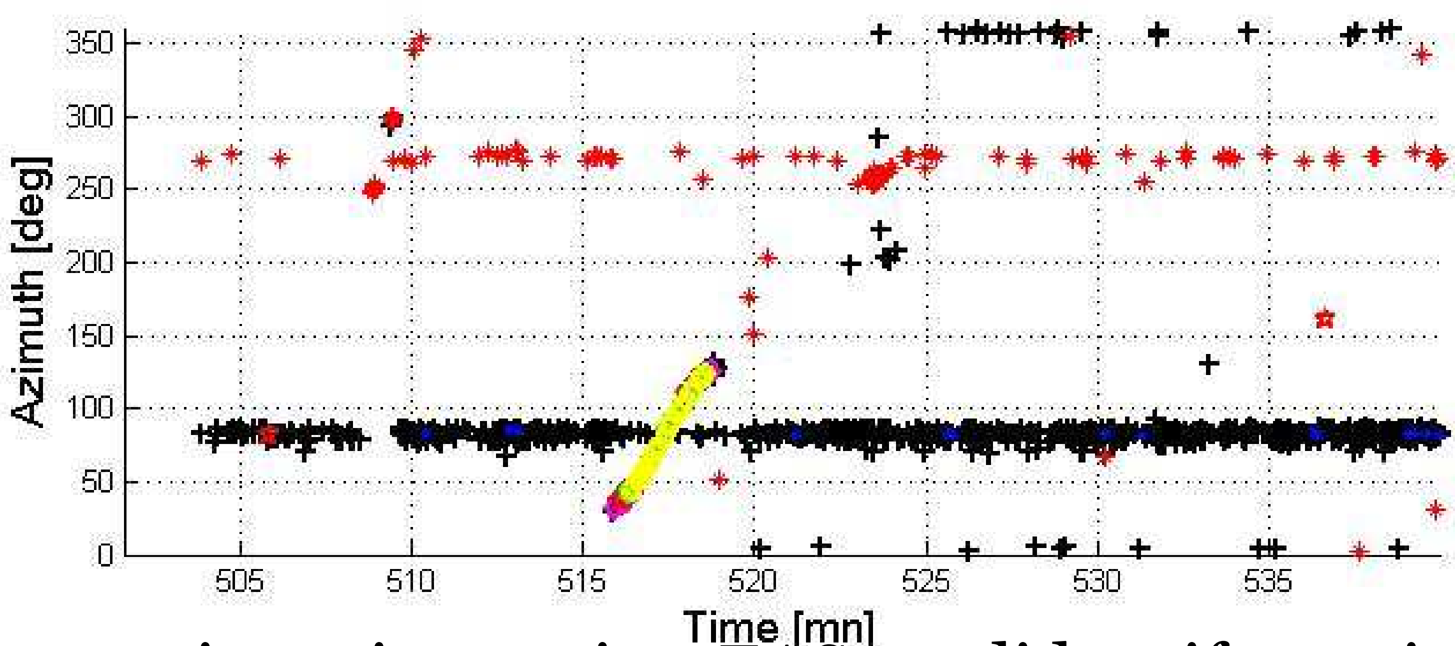




Limited array size + monopolar antennas

Environment cuts

- Bckgd events strongly correlated in time & space



- <u>Consecutive coincs:</u> reject EAS candidate if 1+ coinc with 4+ antennas in common within 30s.
- <u>Same direction events:</u> reject EAS candidate if 1+ coinc with 2+ antennas in common and $|\Delta\varphi|<10°$ within 10 minutes.

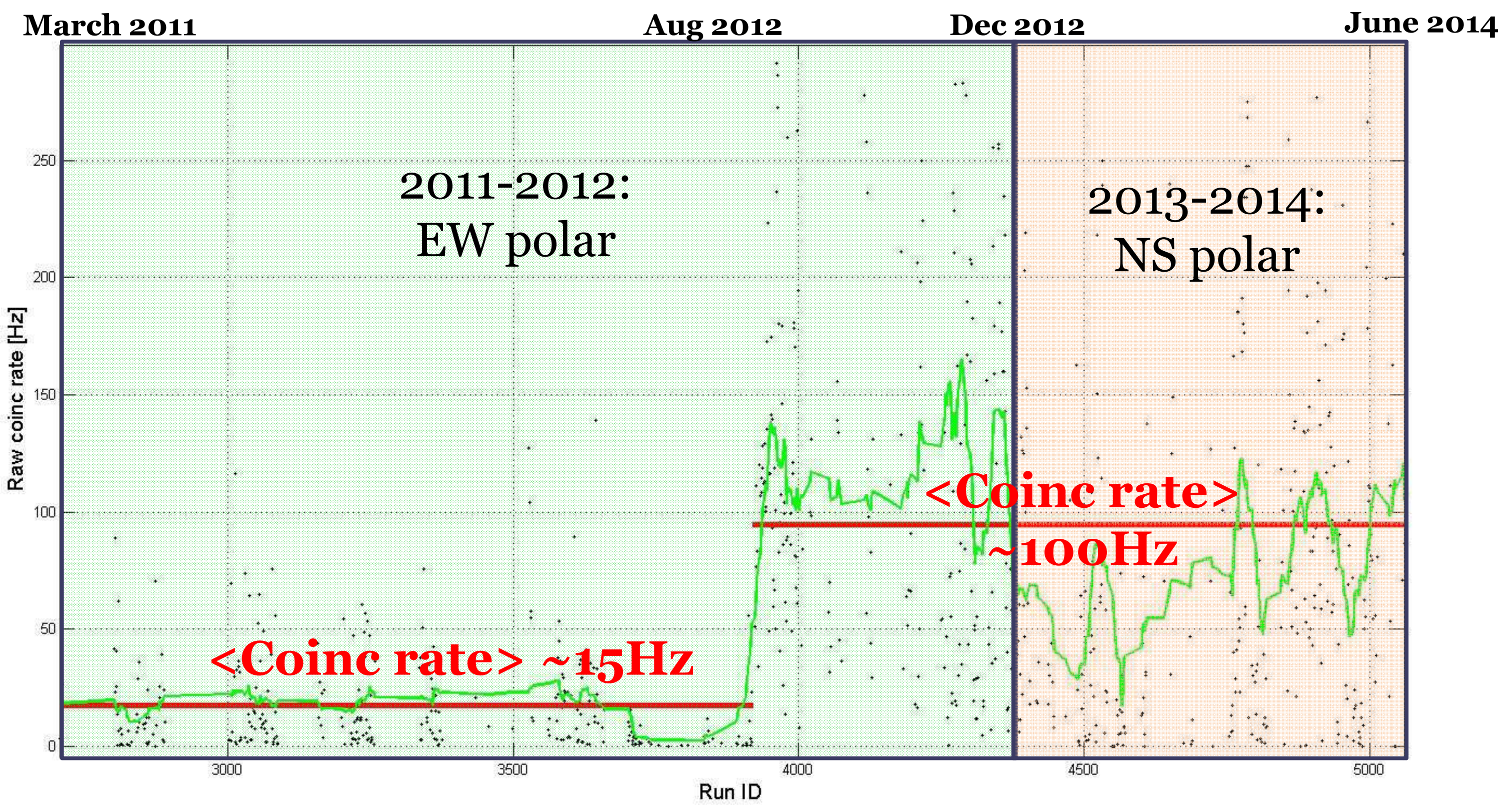
Cut efficiency:
from 2.4 10^8 to 465 events

Cut	% survival	N_{coincs} final	Simu % survival
« 50Hz » cut	24%	5.9 10^7	To be determined
Pulse duration	56%	3.3 10^7	100%
Multiplicity > 4	57%	1.9 10^7	-
Valid direction reconstruction	79%	1.5 10^7	100%
Radius > 3000m	33%	5 10^6	92%
$\Theta < 80°$	14%	7 10^5	/
Trigger pattern/ Extension	15%	10^5	85%
Neighbourgs (direction)	**3%**	2600	To be determined
Neighbourgs	18%	465	To be determined

No cut is related to wave (absolute) arrival direction.

TREND-50 2013-2014

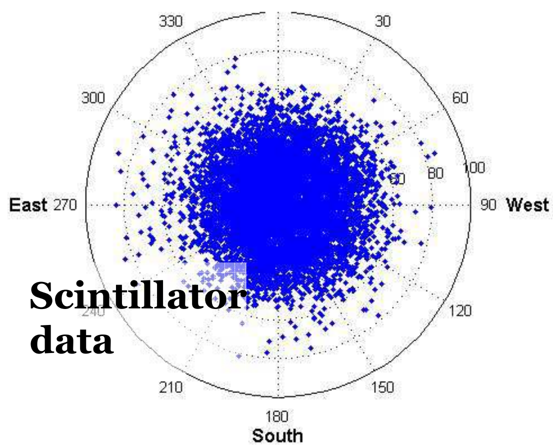
- Possible causes for much fewer candidates:
  - Array maintenance degraded (>30% antennas off)
  - Bckgd noise significantly higher, affects DAQ duty cycle & acceptance (environment cuts)



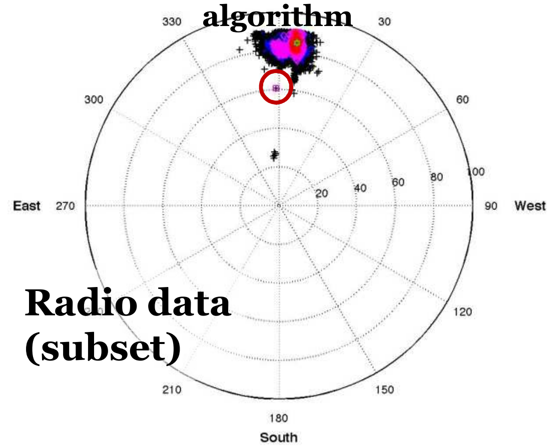
TREND early days (2009-10)

- 2009: 6 log periodic antennas : reconstruction algorithm development + autonomous trigger proof of principle.
- 2010: 15 log-periodic antennas + 3 scintillators: independant trigger & analysis of scint data (EAS) & r[...] lida

Reconstruction of 3-fold scintillator coincidences ≡ EAS



Selection of radio EAS candidates with dedicated algorithm

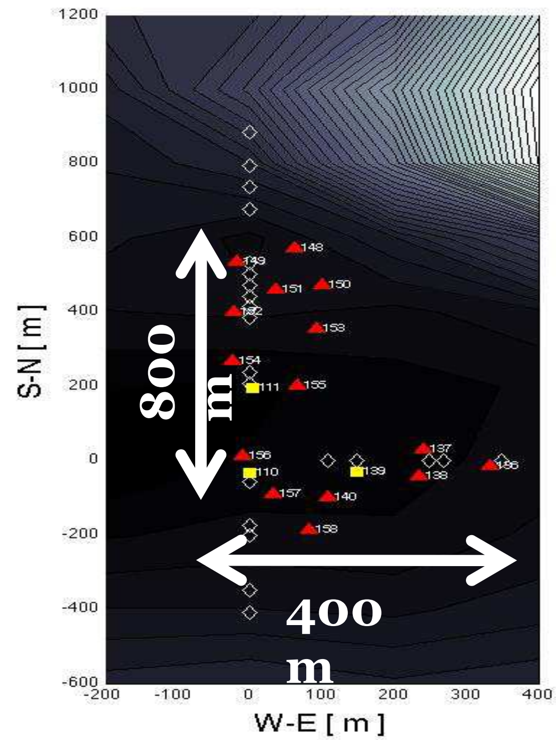


Some radio EAS candidates are coincident with scintillator coincidences + direction recons match!

N_{ants}	θ_{radio}	θ_{scints}	ϕ_{radio}	ϕ_{scints}
4	61±3	67±5	359±2	3±4
4	52±1	49±3	195±2	191±4
5	42±1	36±3	55±4	56±5
4	45±1	49±3	12±1	10±5
7	56±2	53±4	323±2	331±5

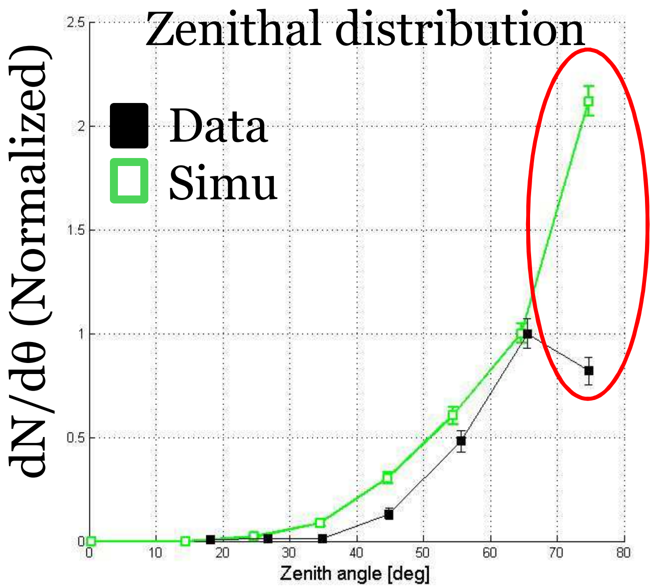
First EAS identification with autonomous radio array

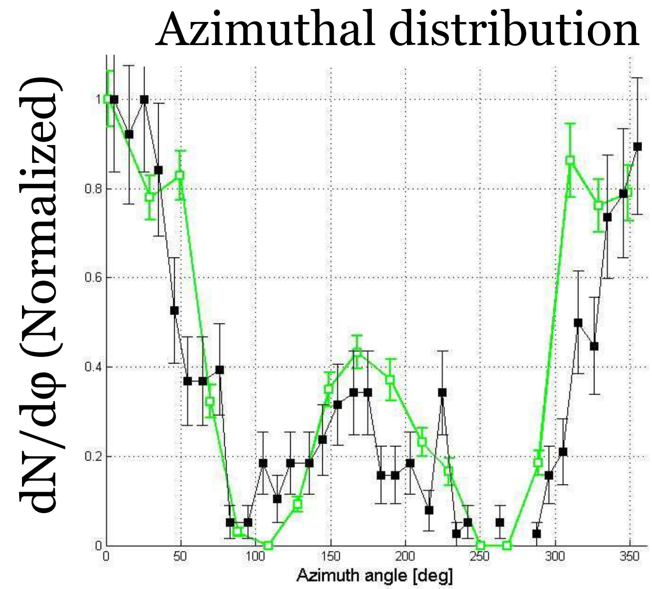
Ardouin et al., Astropart. Phys 34, 2011 <arXiv:1007.4359>

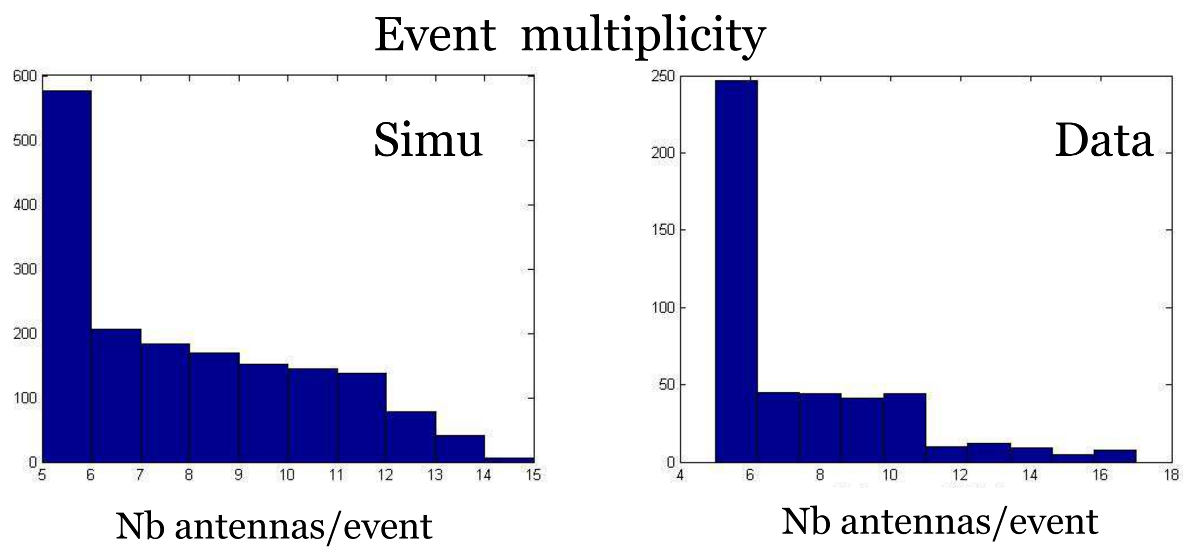


Data-Simu comparison

- Combining 8.10^{16} & 10^{17}eV simulated data sets.
- Comparable zenithal, azim and multiplicity distributions (except for very inclined showers: reflexion issues or cuts?)
- Expected nb of events for threshold = 10^{17}eV: ~6000 in 317 days <u>before analysis cuts</u>. 465 observed…
Detection efficiency <10%







MC

ToDo: full MC simulation

- Simulate EAS events with proper distributions in flux, direction, core positions & energies.
- Generate expected antenna response to these EAS events at fixed random times.
- If 5+ triggers, insert these simulated events in experimental data (after experimental EAS candidates have been removed).
- Process these data through standard analysis chain.
- Produce simulated maps & compare to data

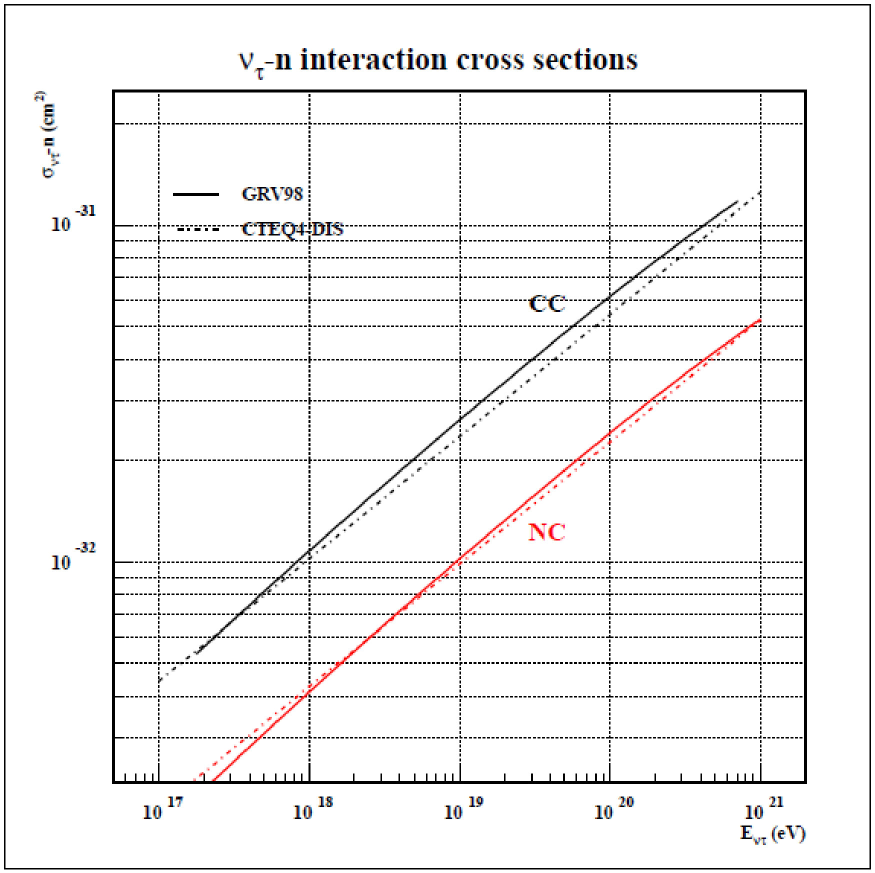
  -> Background rejection performances

  -> Detection threshold

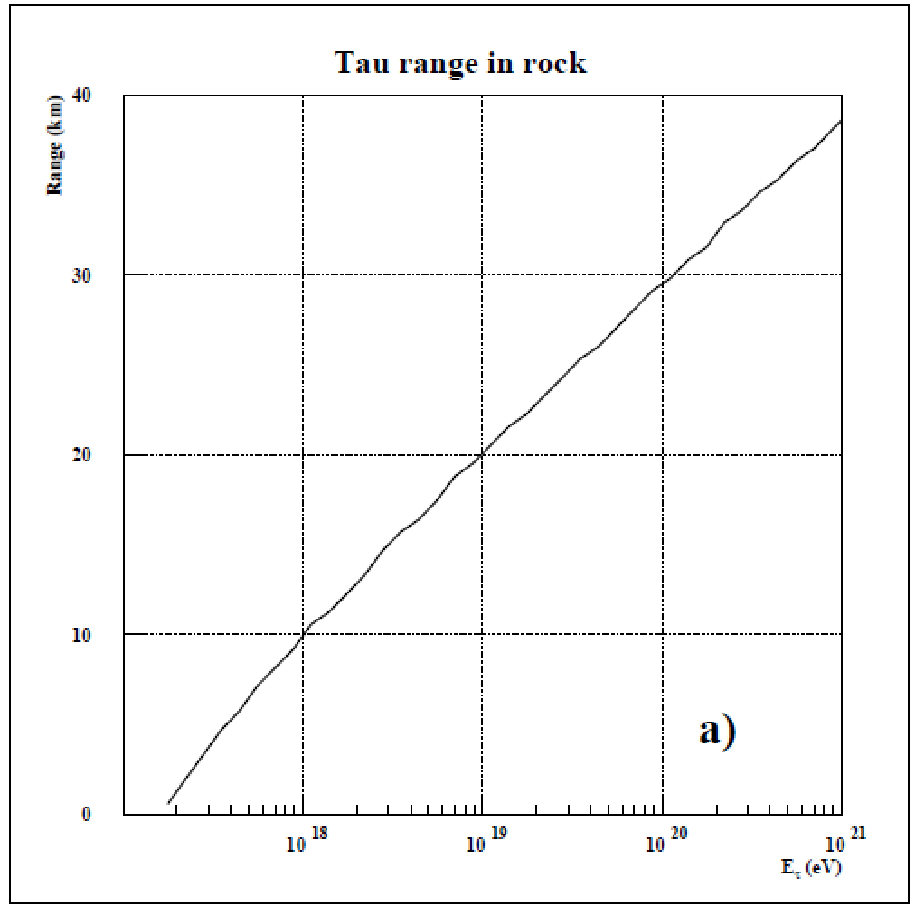
  -> Detection efficiency

The neutrino simulation ingredients

- ν **Deep Inelastic Scattering (DIS)** in the rocks:
  - Integrated cross sections from Gandhi et al. (CTEQ4-DIS), but inelasticity randomised with Pythia CTEQ5d pdf.
  - The neutrino is tracked until a CC interaction occurs, its energy falls below a threshold (1 PeV typically) or it escapes the simulation volume.
- τ **propagation in rocks (energy loss+proper time)** :
  - **Detailed studies** of the τ energy loss in rocks **with GEANT4 simulations** for various τ initial energies. The τ photonuclear interactions, dominant energy loss process at UHE, have been coded in GEANT4 following Dutta et al.
  - **Parameterisation** of the τ energy loss and of the proper time spectrums according to the distance d (0-60 km) and the initial energy, E_0.
  - For the simulation, use an **hybrid Monte-Carlo scheme** for the τ propagation in rocks (energy loss, decay) according to the parameterisations derived from GEANT4.
- τ **decays** :
  - Simulated with Pythia+TAUOLA.
  - The decay daughters are logged to a file which would be served as input to the shower simulation. The daughter ν_τ is further simulated.

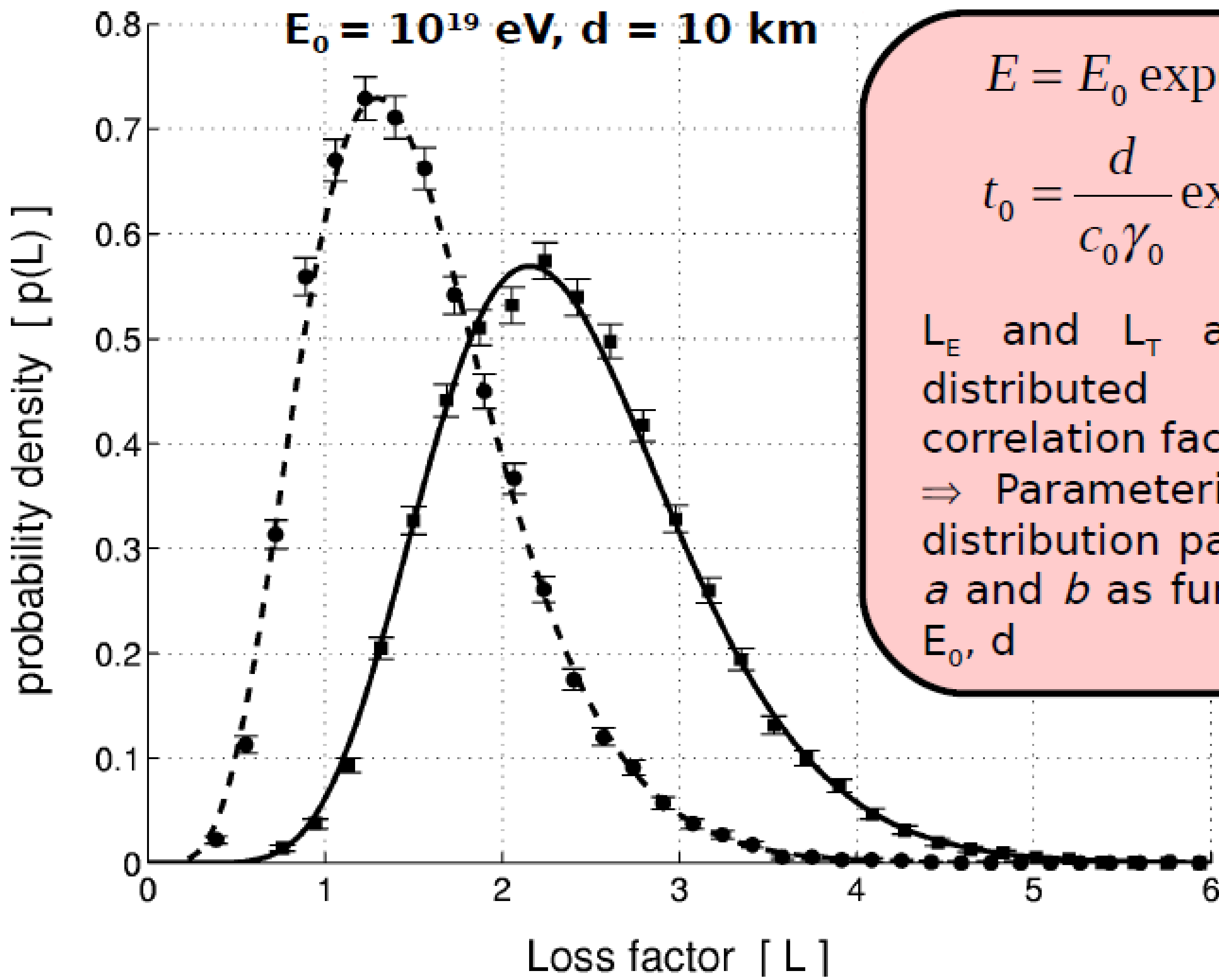


ν_τ-n interaction cross sections
$\sigma_{\nu\tau\text{-}n}$ (cm^2)
10^{-31}
10^{-32}
GRV98
CTEQ4-DIS
CC
NC
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
$E_{\nu\tau}$ (eV)



Tau range in rock
Range (km)
40
30
20
10
0
a)
10^{18}
10^{19}
10^{20}
10^{21}
E_τ (eV)

Parametrisation of τ energy loss and proper time in Standard rocks

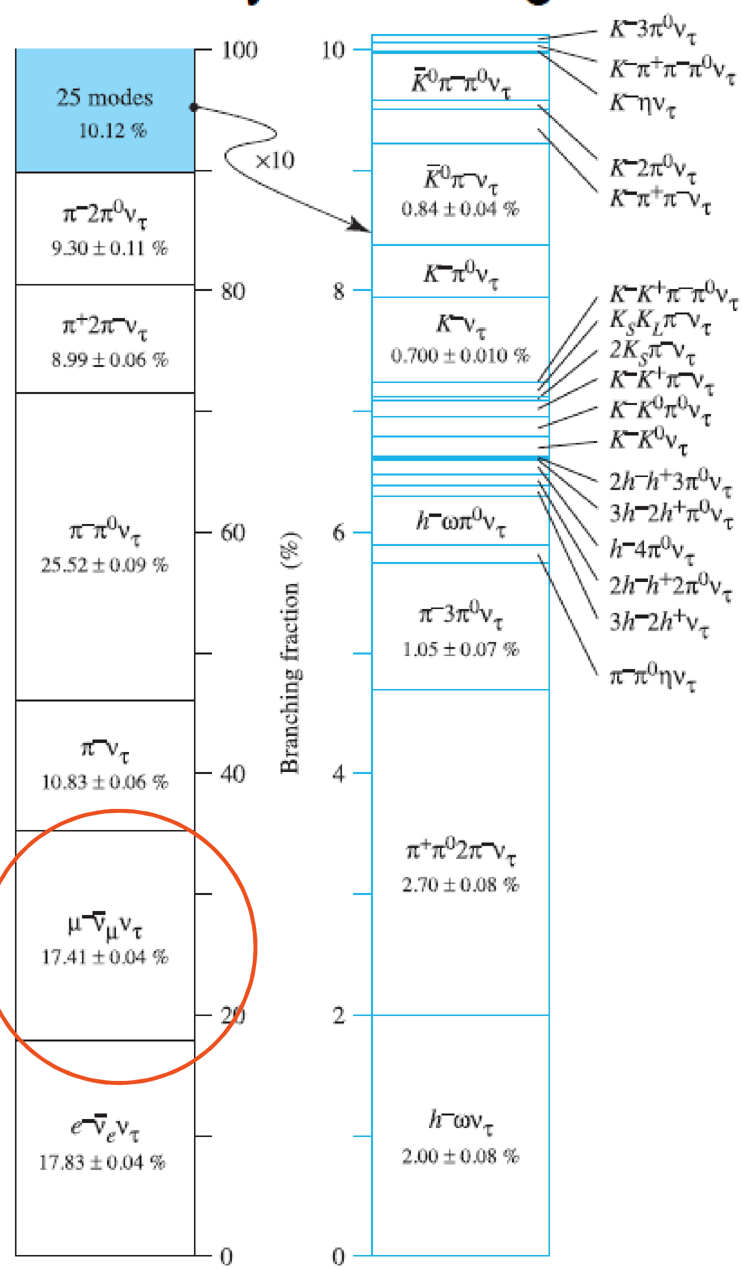


$$E = E_0 \exp(-L_E)$$

$$t_0 = \frac{d}{c_0 \gamma_0} \exp(L_T)$$

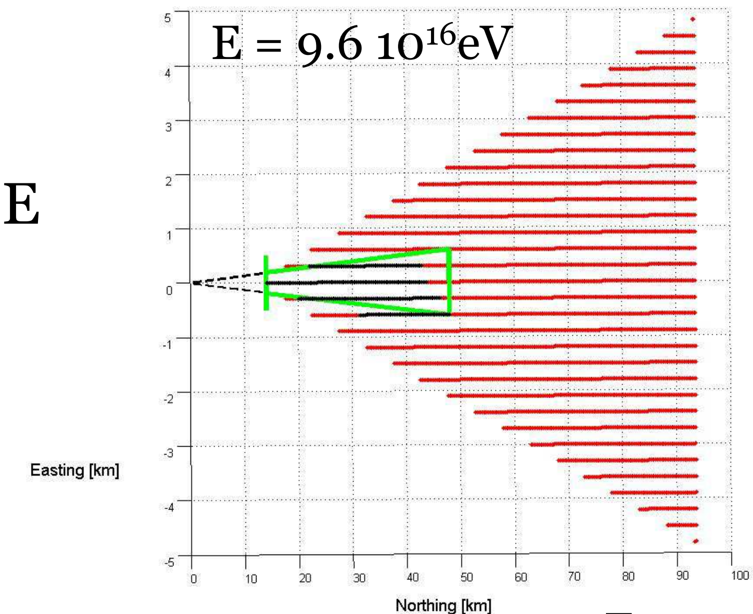
L_E and L_T are $\gamma(a,b)$ distributed with a correlation factor ~ 0.9
⇒ Parameterise the γ distribution parameters *a* and *b* as functions of E_0, d

τ decay branching ratio

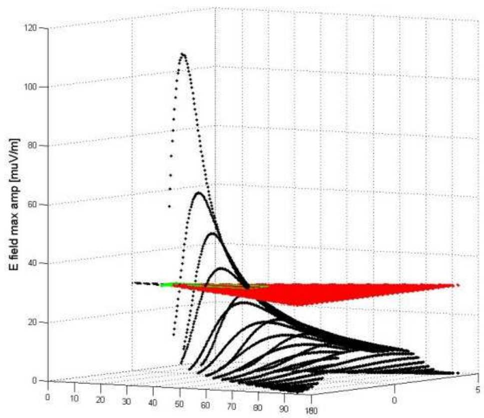


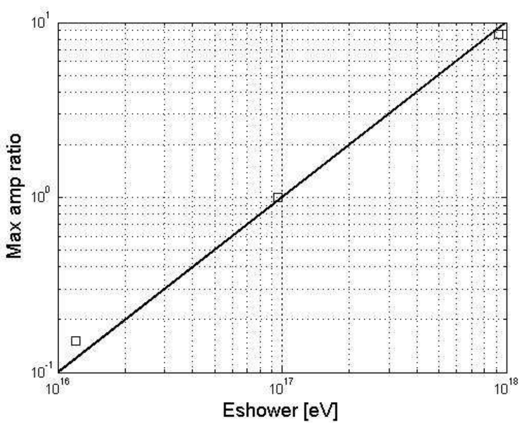
GRAND shower parametrization

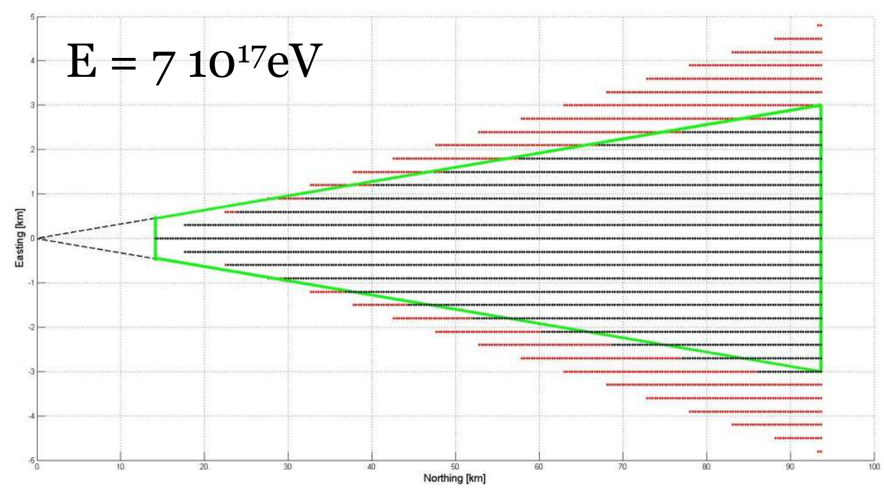
- Conical parametrization
- ONE simulated shower ($E = 10^{17}$eV) , amplitude scaling with E



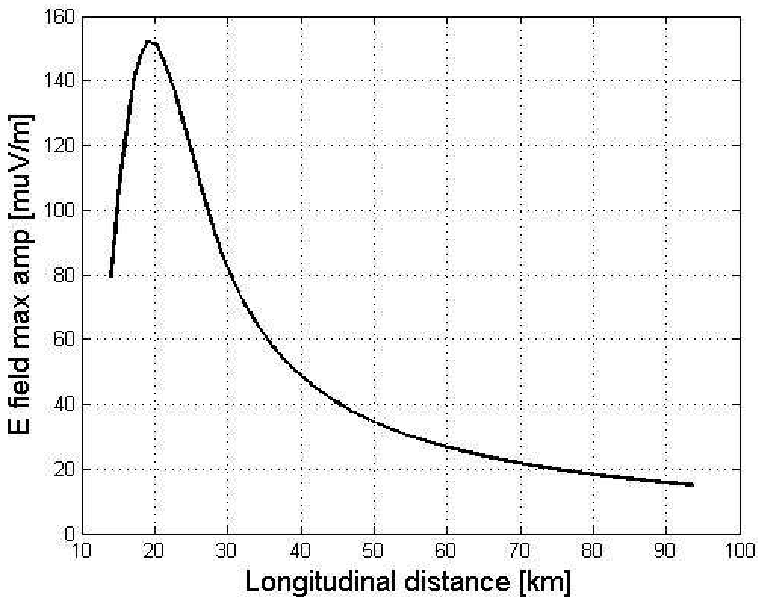
$E_{th} = 30\mu V/m$

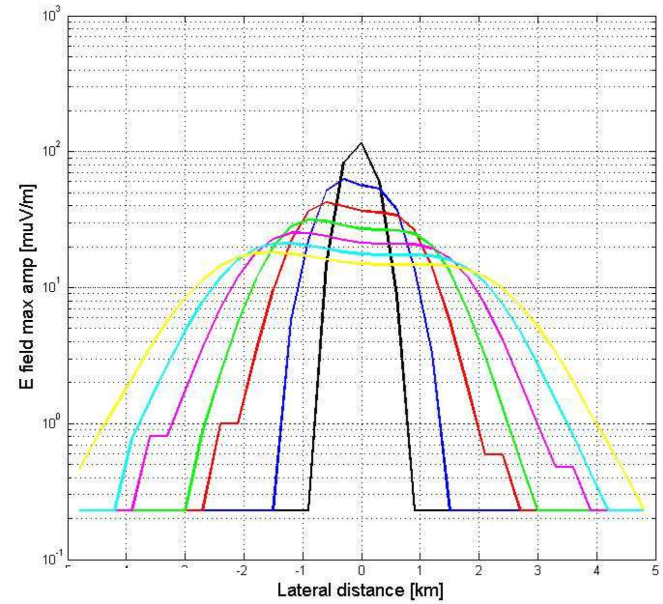


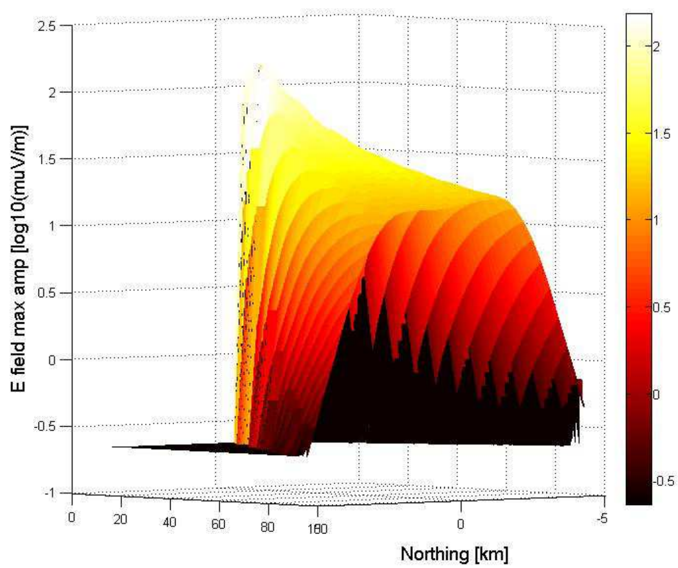




ZHAireS shower profile

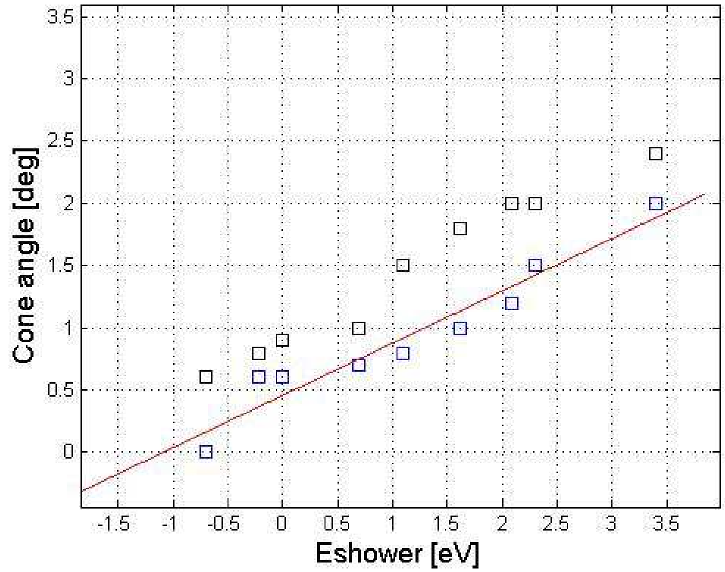


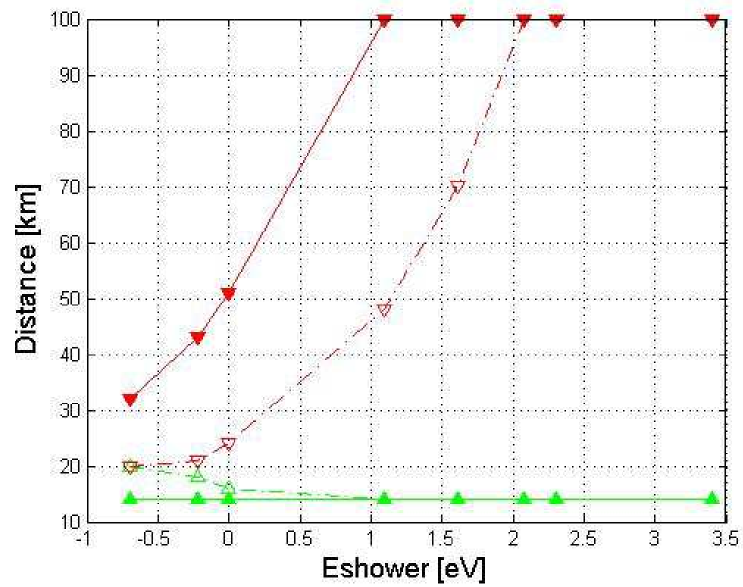




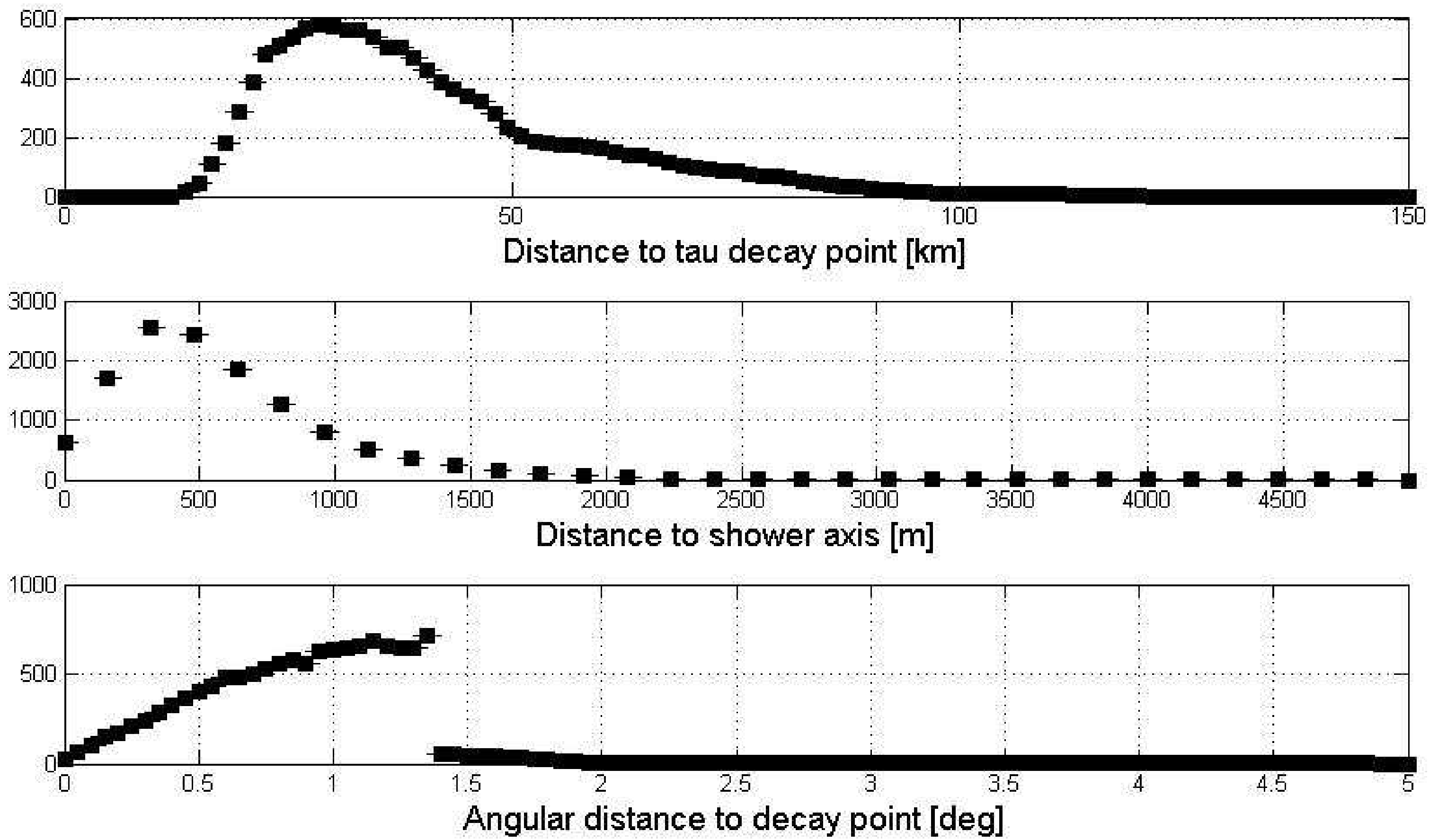
Detection parametrization

- Agressive:
  - Detection if Efield>30μV/m
  - α = min(1.4°, cone half angle)
  - Distance to decay point in [14, 50->120]km
- Conservative
  - Detection if Efield>100μV/m
  - α = cone half angle
  - Distance to decay point in [14, 50->120] km



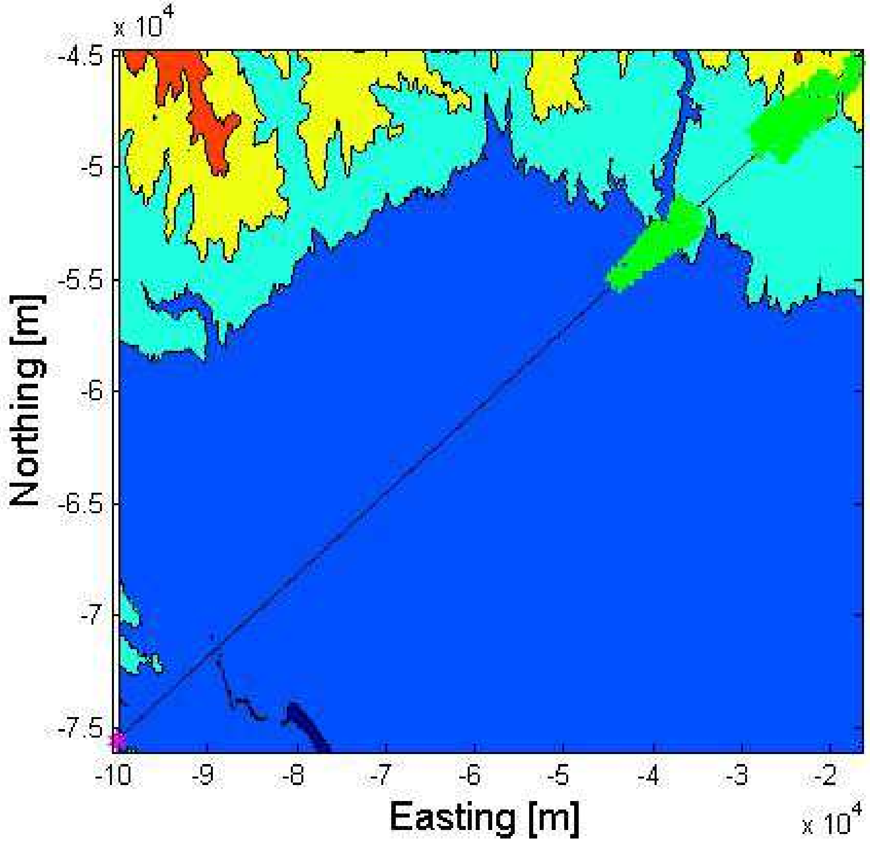


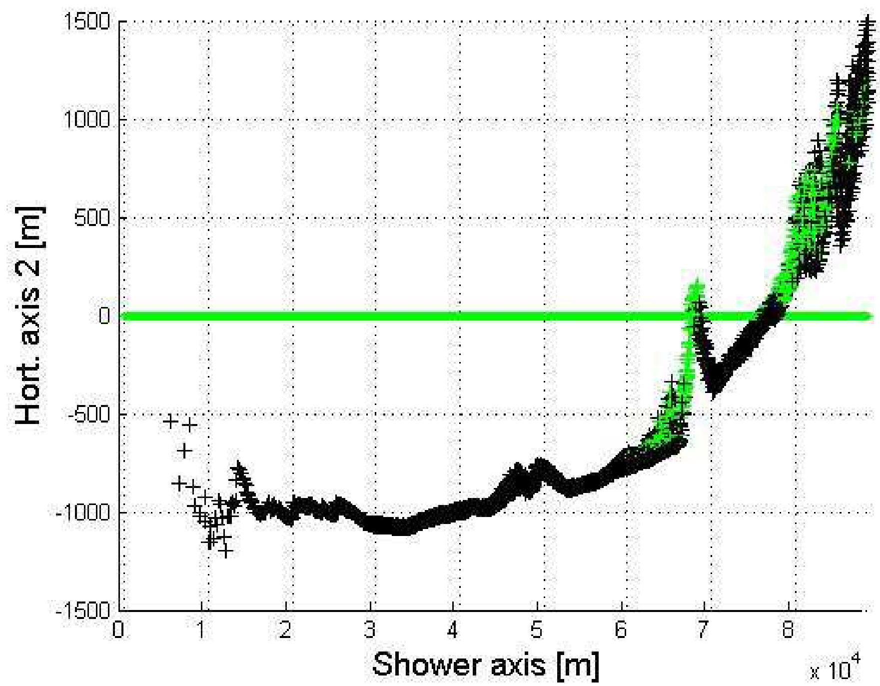
Simulation results



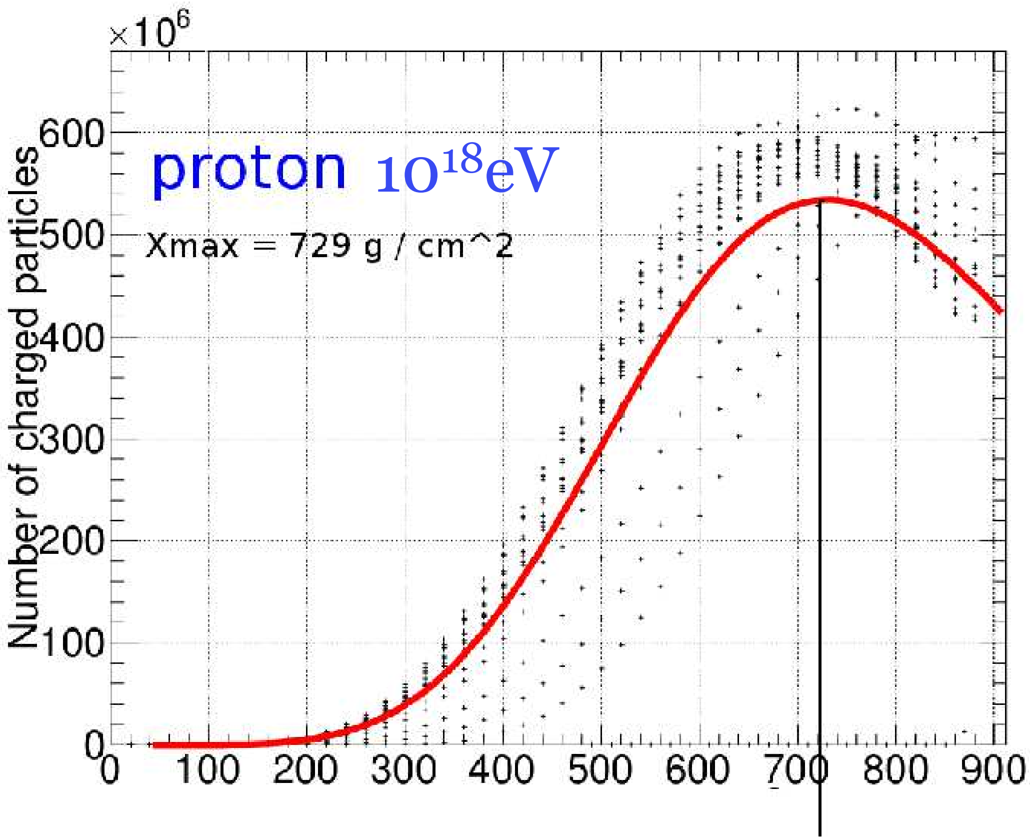
TREND EAS detection criterium(1): shower topology

- Consider **shadowing effect** (only antennas in direct view of s
- Discard isolated antennas ($d_{closest}$>2km)
- Request 1+ cluster with 5 antennas at least.





GRAND EAS detection criterium (2): minimum distance to shower



@ 2000m asl: ρ = 0.1 g/cm3
atm depth [g/cm²] ⇔ 0.1xlength [m]

Minimum shower distance:

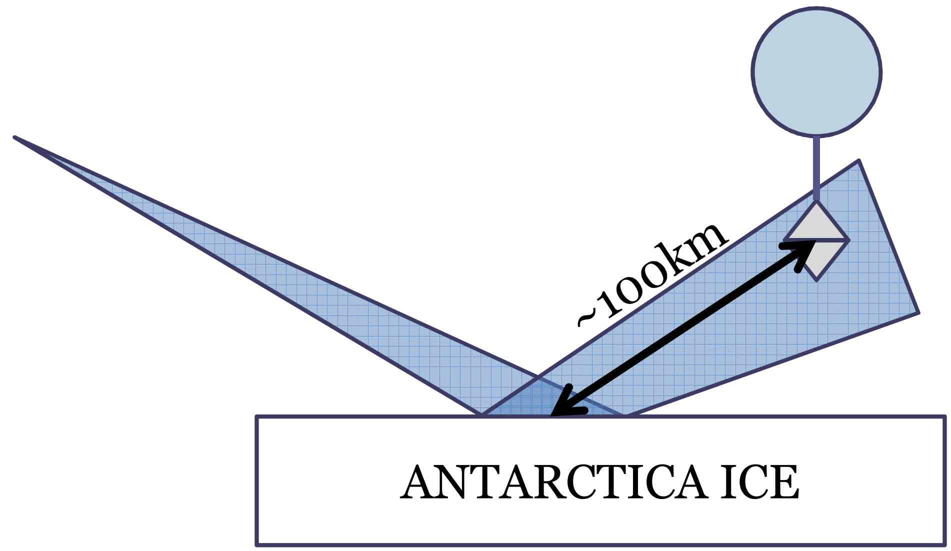
- Shower has to be distant enough to develop and produce enough e^+/e^- to generate sizeable electromagnetic field.
- **5km** seems reasonable.

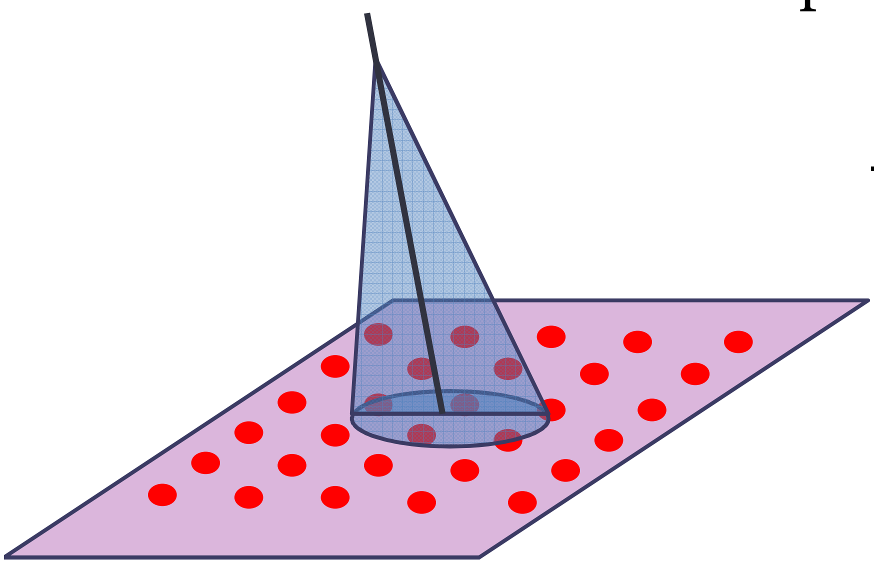
TREND EAS detection criterium (3): maximum distance to shower

- Experimental situation

– ANITA

- Baloon-borne experiment above the Antarctic.
- Detection of 16 EAS (14 reflected on the ice surface) with <E>=1.5 10^{19}eV, <d> ~100km from reflexion point.

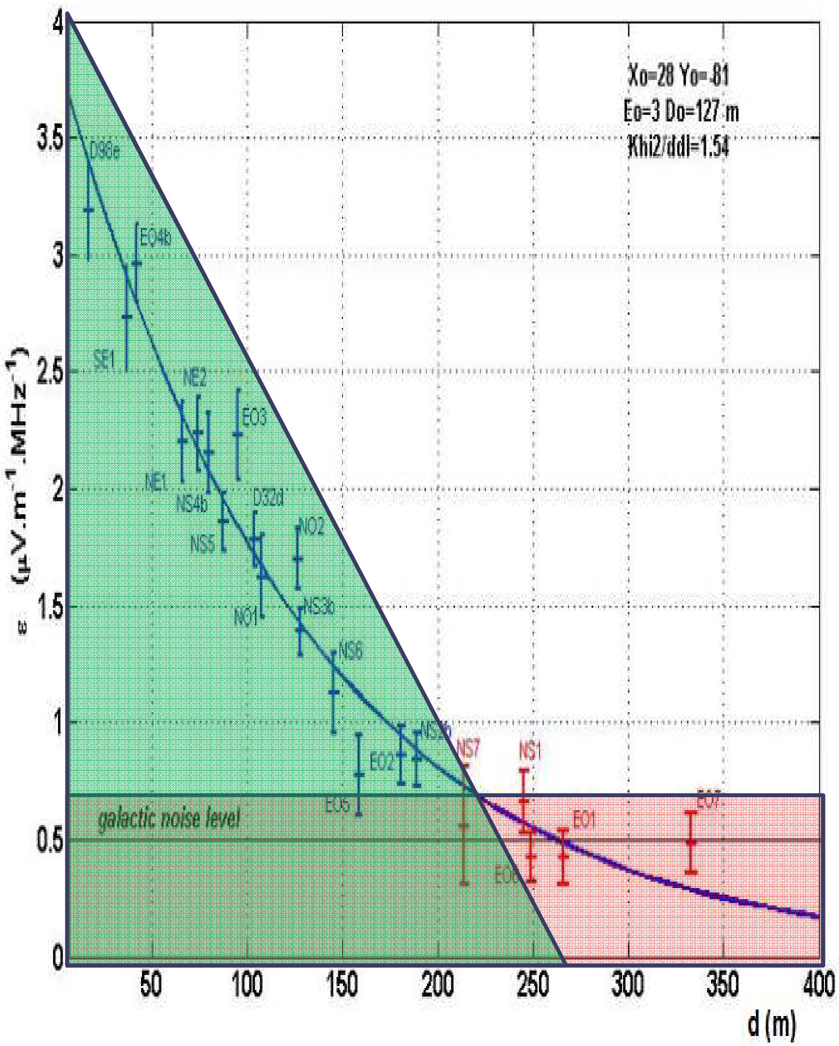




– CODALEMA

- Array of radio antennas on ground
- Detection of 10^{17}eV showers (with ε=85%) ~ 300m away from axis.
- $\varepsilon(d) = k\varepsilon_o \exp(-d/d_o)$ and $\varepsilon \propto E$

GRAND ν sensitivity study - Parameters



- « Detection cone » inside which antennas trigger.
- CODALEMA:

  $\tan\alpha(10^{17}\text{eV}) = 250/7000\text{m} = 3°$
- Linear scaling of Efield with EAS energy

$\varepsilon(d) = \varepsilon_o \exp(-d/d_o)$

$\varepsilon(d_{th}) = kE \exp(-\tan\alpha_{th} / \tau)$ with $\tau = d_o/L$

$$\tan\alpha_{th} = \tau \ln\left(\frac{E}{10^{17}}\right) + \tan\alpha^{17}{}_{th}$$

- ANITA: radio triggers @ ~10^{19}eV at distances > 200kms

TREND detection criterium (3)

- α_{th}^{17} ?

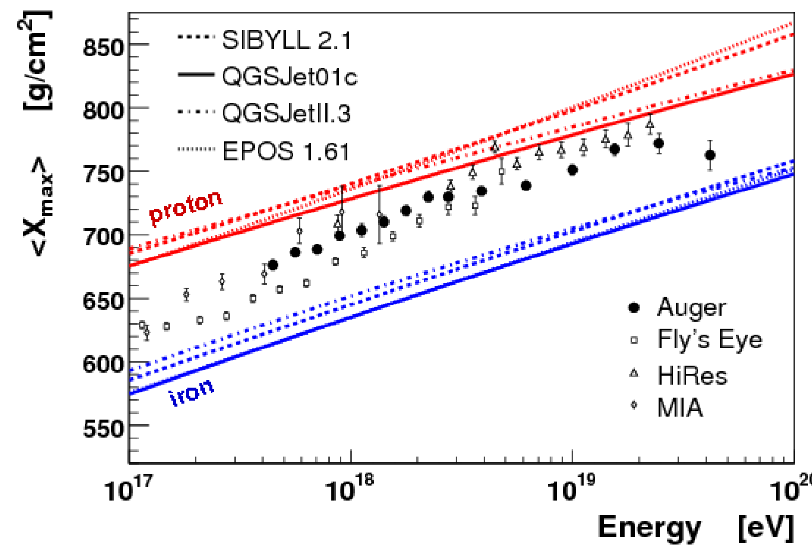
CODALEMA showers:

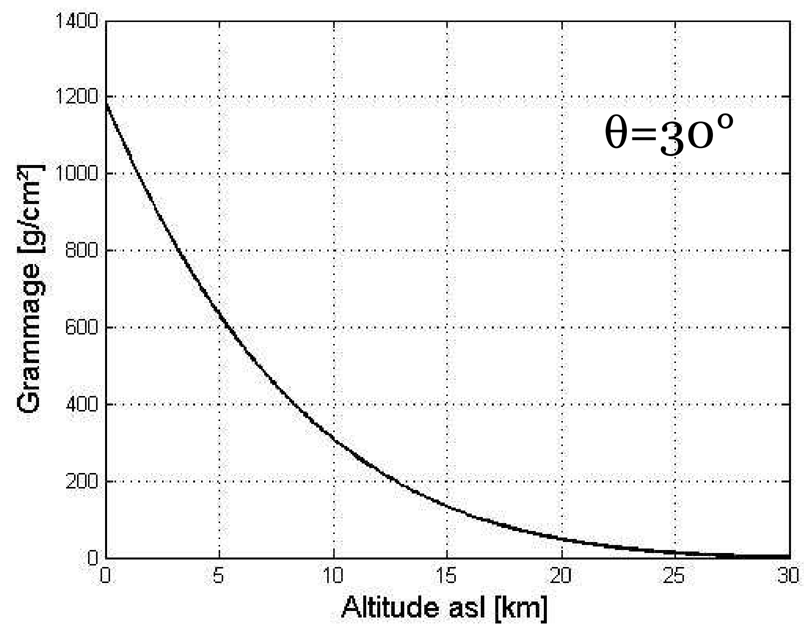
  - d_{max} ~ 300m (CODALEMA)
  - X_{max} ~ 630g/cm² @ 10^{17}eV and <θ>=30° ➡ L~6000m

➡ α_{th}^{17} = atan(d_{max}/L) ~ 3°

- τ?
  - d_0 in [100,400m for L~6000m] (CODALEMA)

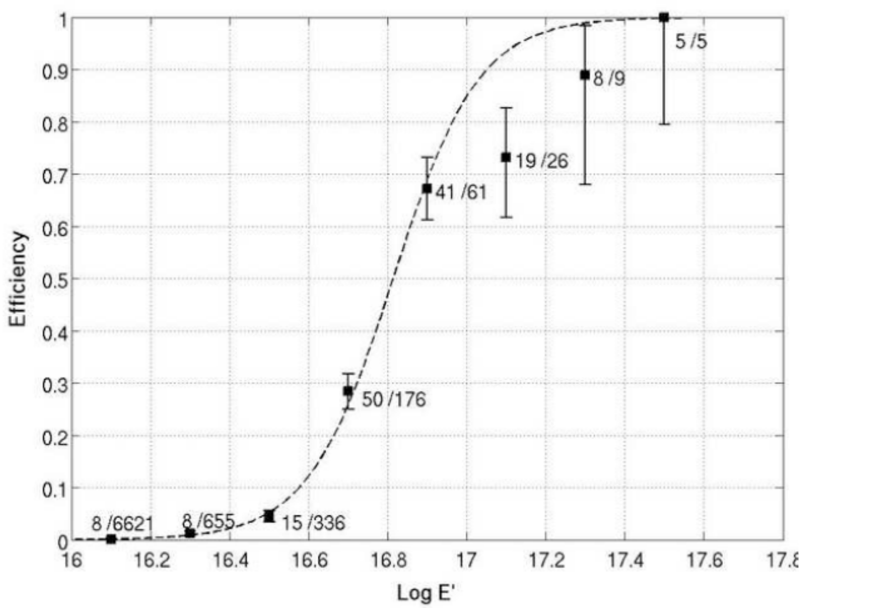
➡ τ = d_0/L in [0.017, 0.067]





TREND EAS detection criterium (4): minimum shower energy

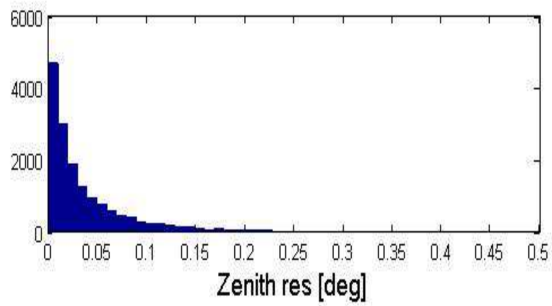
- $E_{threshold}$?
  - CODALEMA: ε=85% @ 10^{17}eV.
  - For ~horizontal showers & East-West+North-South measurements, geomagnetic effect should be more efficient.
  - Beamed emission + low attenuation: threshold should not be affected by distance to shower.

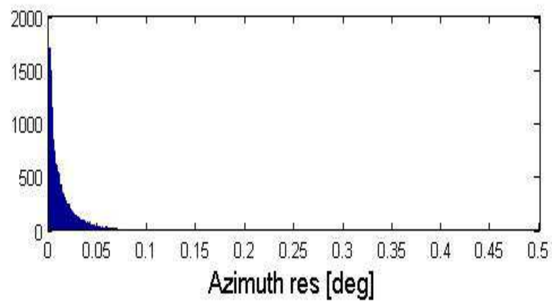


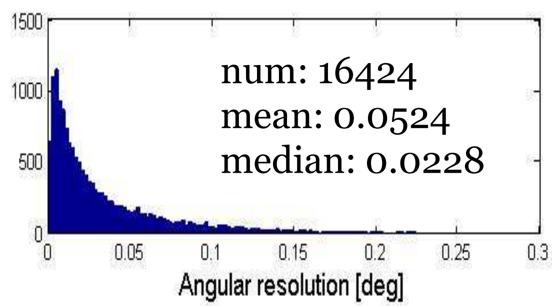
E_{th} in [3.10^{16}, 3.10^{17}] eV

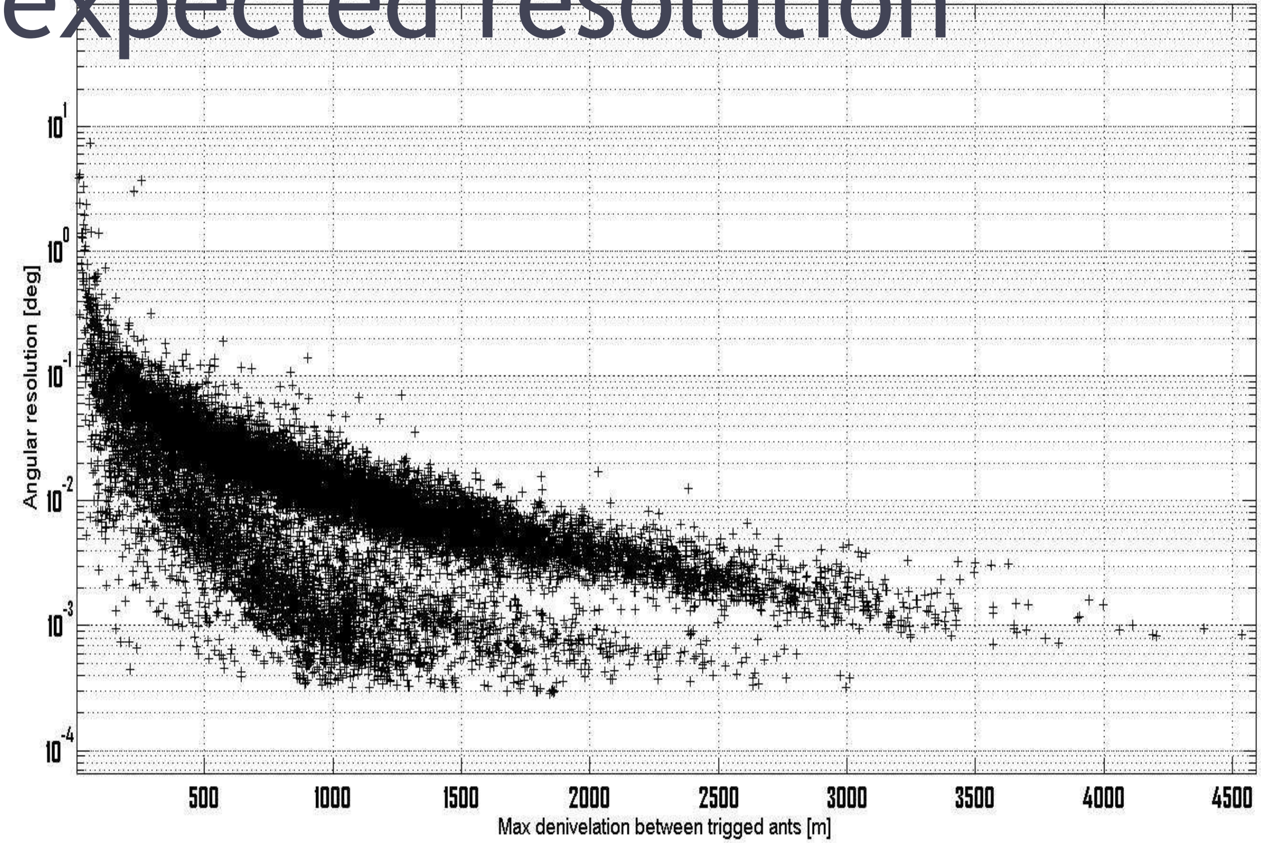
GRAND expected resolution

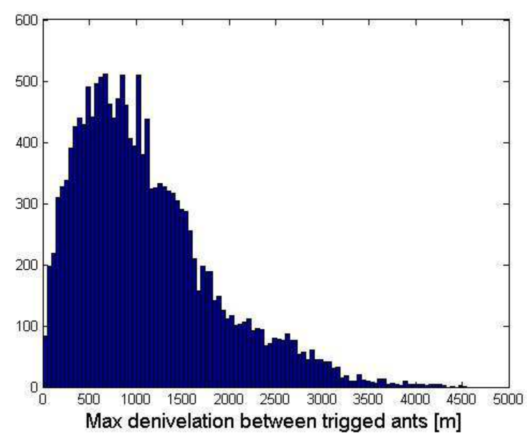
Cut out events with max deniv<100m
(2% of events)

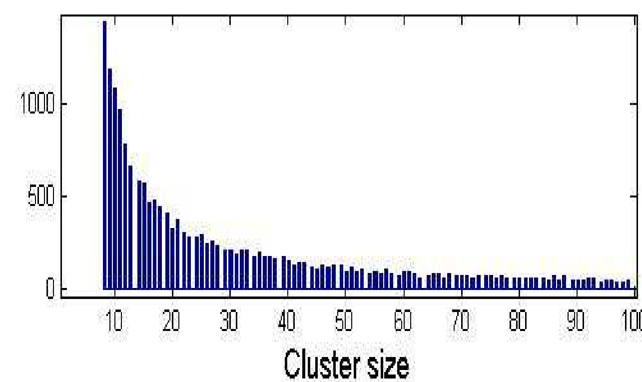


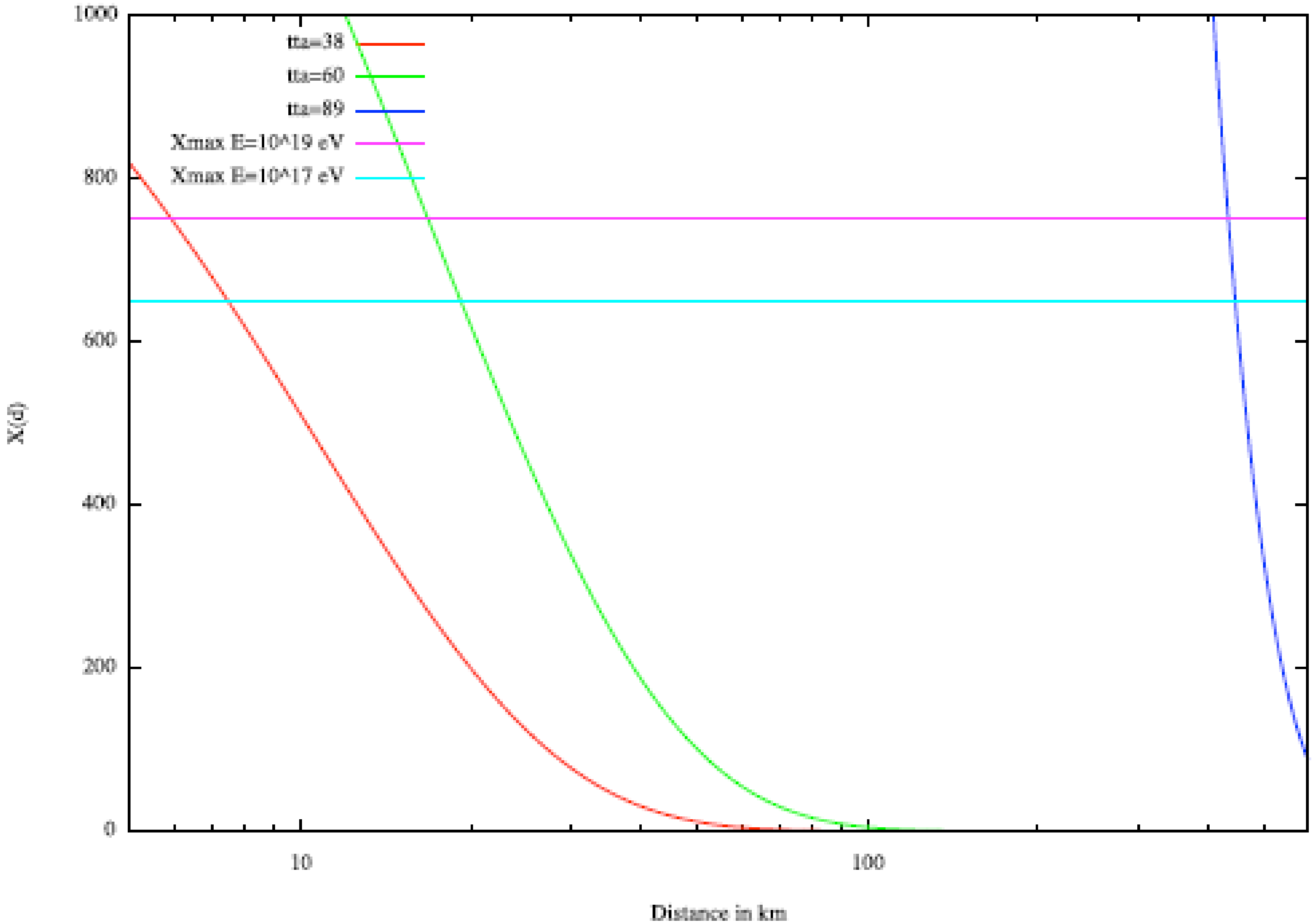












1000
800
600
400
200
0
X(d)
10
100
Distance in km
tta=38
tta=60
tta=89
Xmax E=10^19 eV
Xmax E=10^17 eV

- Stefan Jensen, PhD thesis (in preparation)

Table 7.2: Overview of systematic uncertainties of the average depth of shower maximum as a function of bin energy in the selected high quality data set.

$\log_{10}$[E/eV]	17.9	18.1	18.3	18.5
gain calibration [g cm^{-2}]	4.5	4.2	3.7	3.4
parameterization [g cm^{-2}]	20.0	20.0	20.0	20.0
total [g cm^{-2}]	20.5	20.4	20.3	20.3

figure 2.8). In addition, it is compared with the average X_{max} as a function of energy produced by three different interaction models for showers with proton and iron primaries. The statistical uncertainty of the average value can be estimated by calculating the standard error of the average, and is represented in the plot by the error bars.

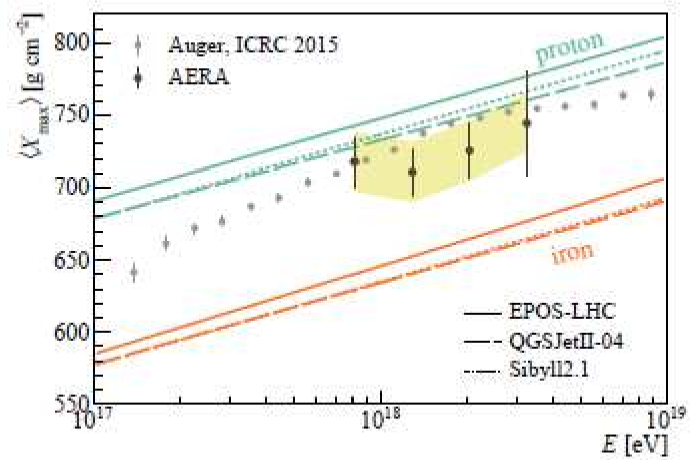
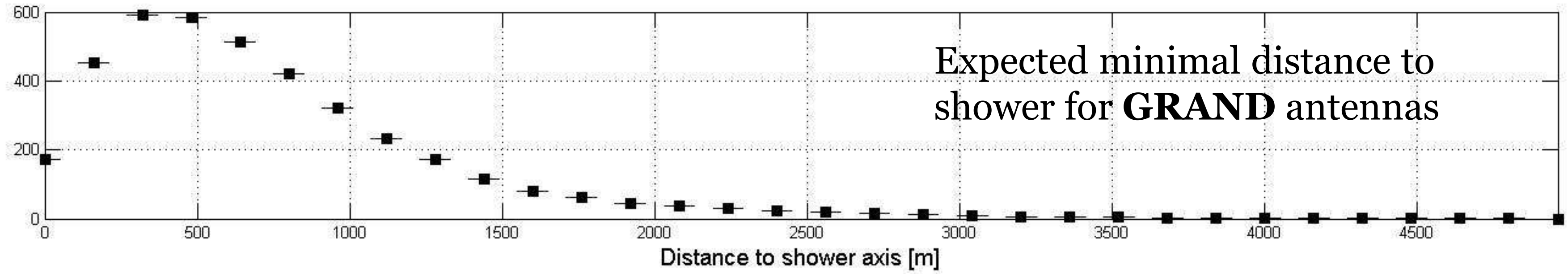
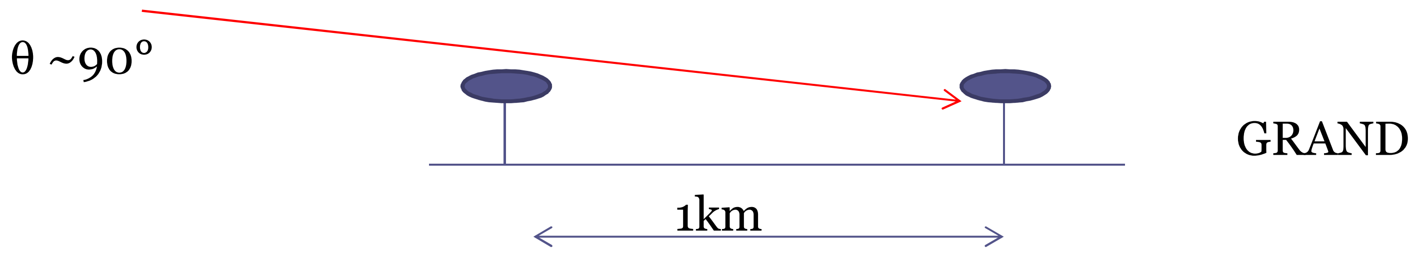


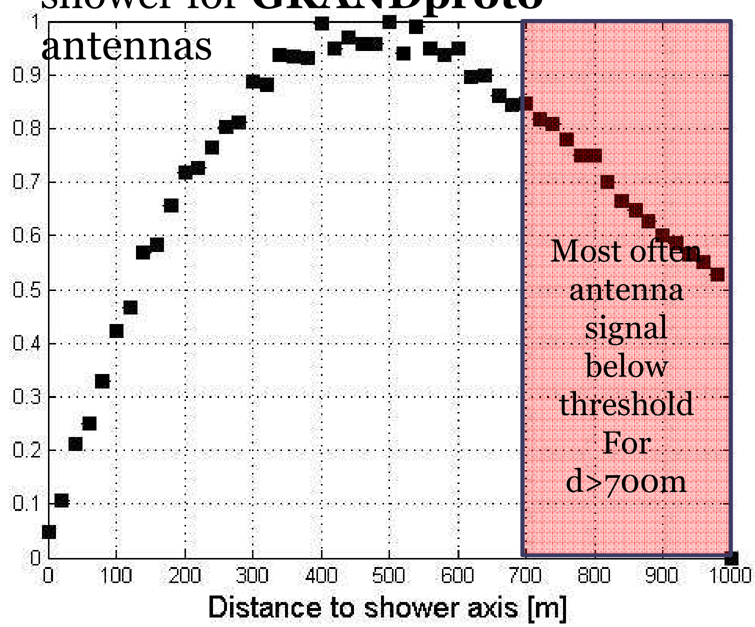
Figure 7.28: Average depth of shower maximum as function of cosmic ray energy as measured by AERA using the spectral index compared with the fluorescence measurements from the Pierre Auger observatory. The error bars of the AERA data points represent the standard error of the average. The colored band indicates the systematic uncertainty. Predictions of the depth of shower maximum of iron and proton primaries from three different interaction models are plotted as lines.

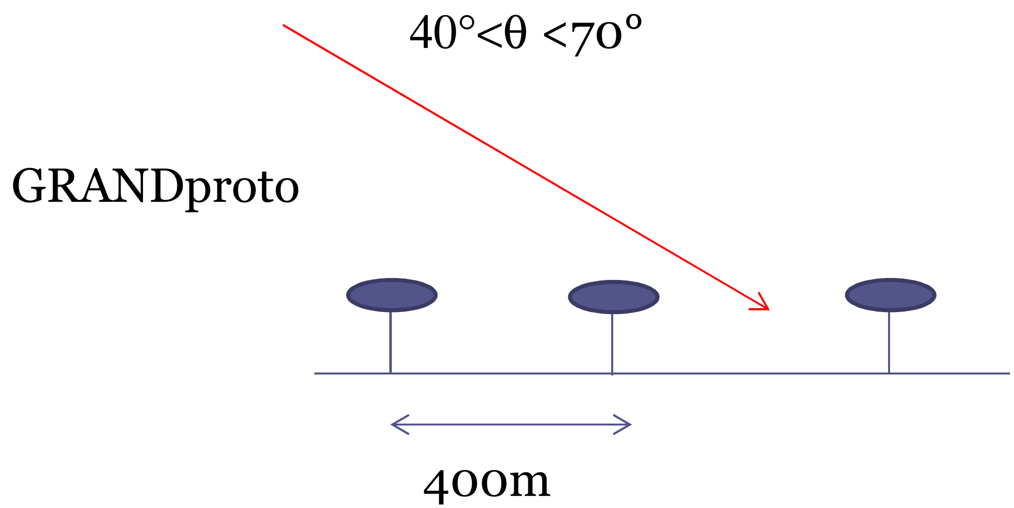
The average depth of shower maximum as a function of energy as measured with AERA using the parameterization of the spectral index of the radio pulse is compatible with the mea-





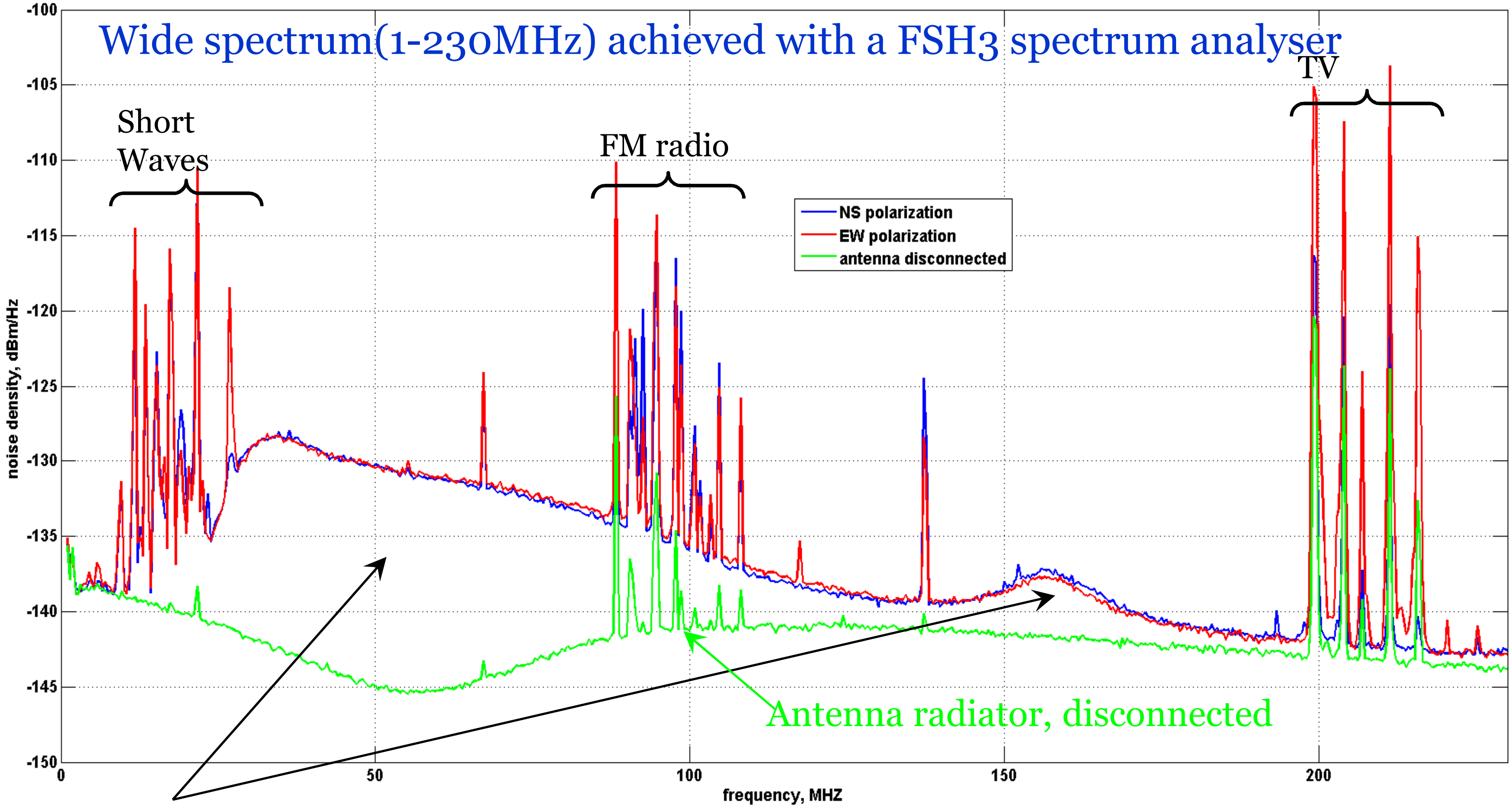
Expected minimal distance to shower for **GRANDproto** antennas





Tech aspects

Spectrum up to 230MHz with the Butterfly antenna at Augers Radio (CLF)

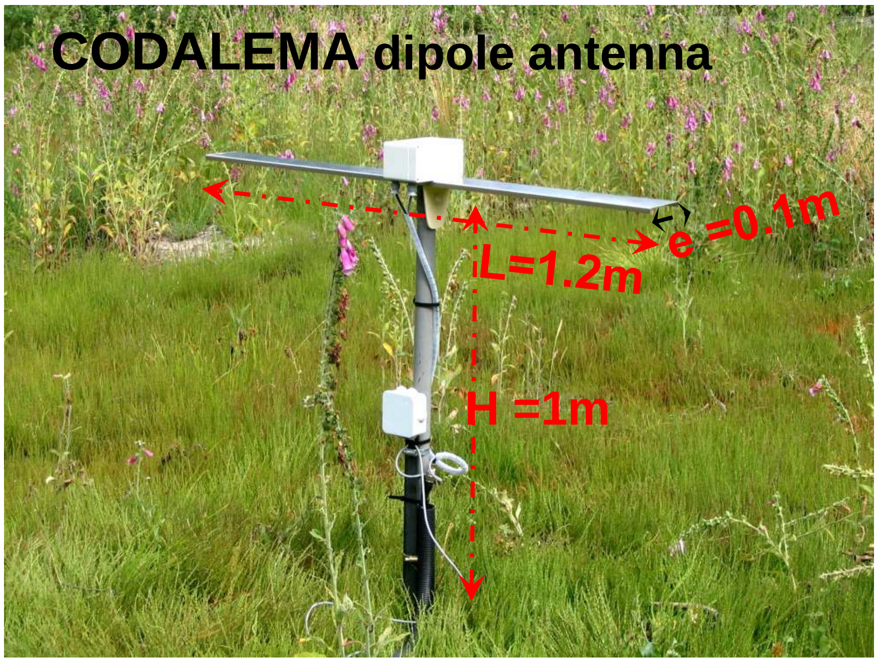


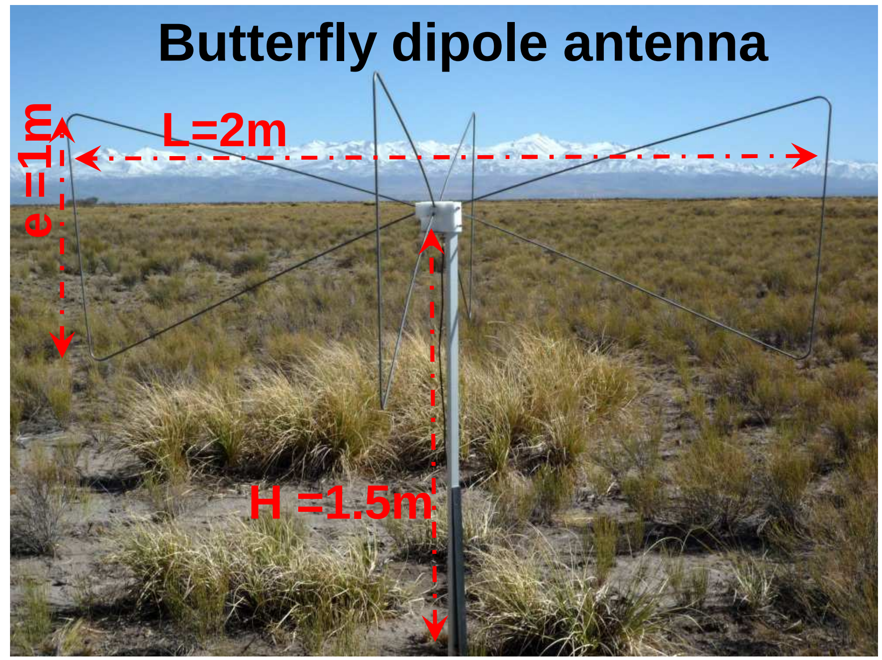
- Galactic background visible up to 170MHz
- Very Quiet area ! : strongest transmitters are only 25dB over galactic background
- ⇒ No intermodulation
- *Good symmetry between North-South and East-West polarization*

CODALEMA active dipole Antenna / Butterfly active dipole antenna

83 Didier Charrier ARENA 2010, June 29 – July 2, Université de Nantes

- **16 dipole antennas and 3 Butterfly antennas are in operation on the field for the CODALEMA experiment (Nançay, Cher, France) since 6 years**
- **3 Butterfly antennas with autonomous station are in operation on the field at Augers Radio (Malargüe ,Argentina) since one month**

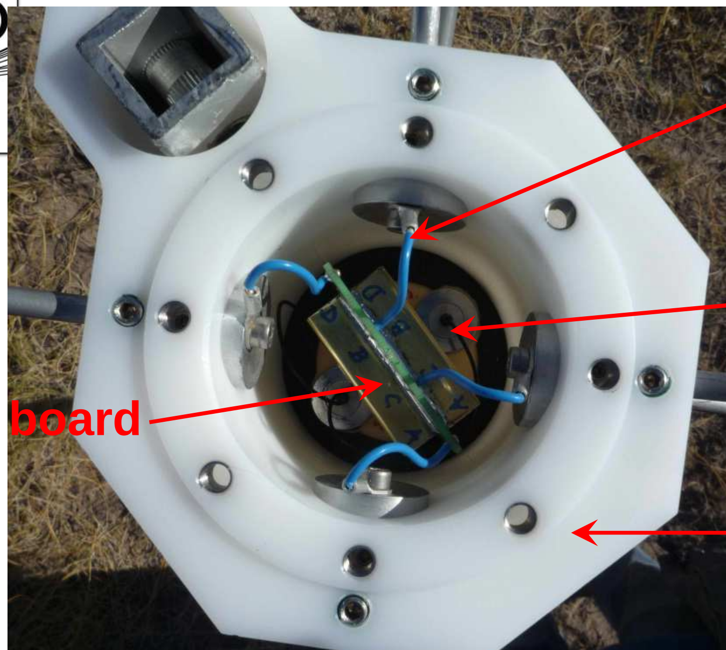


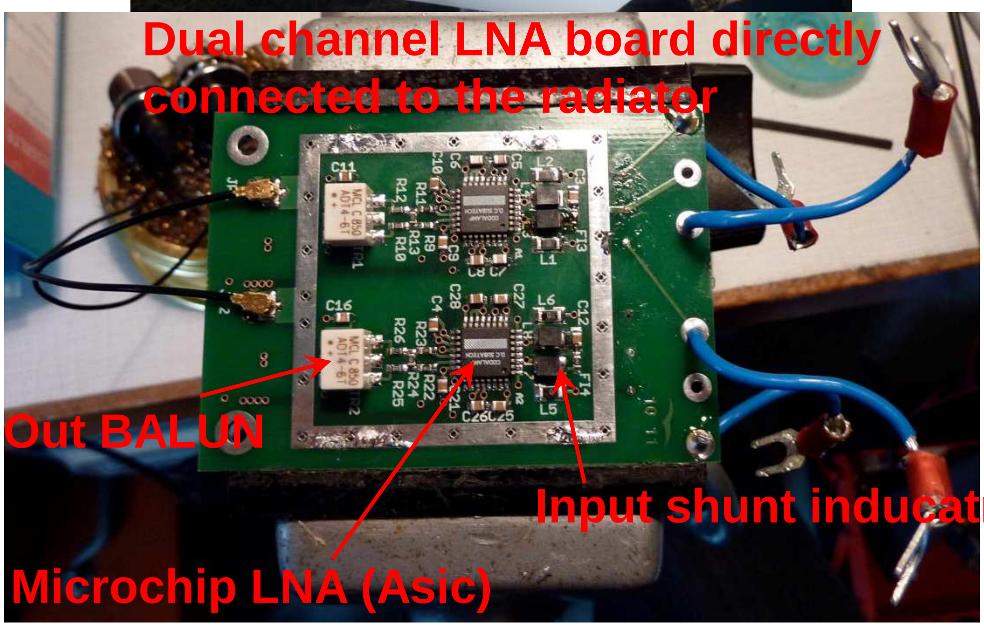


- **Both antennas are fat active dipole**
- **The CODALEMA dipole antenna is mono polarization**
- **The Butterfly antenna is a Dual polarization**

Didier Charrier ARENA 2010, June 29 – July 2, Université de Nantes

LNA board characteristics



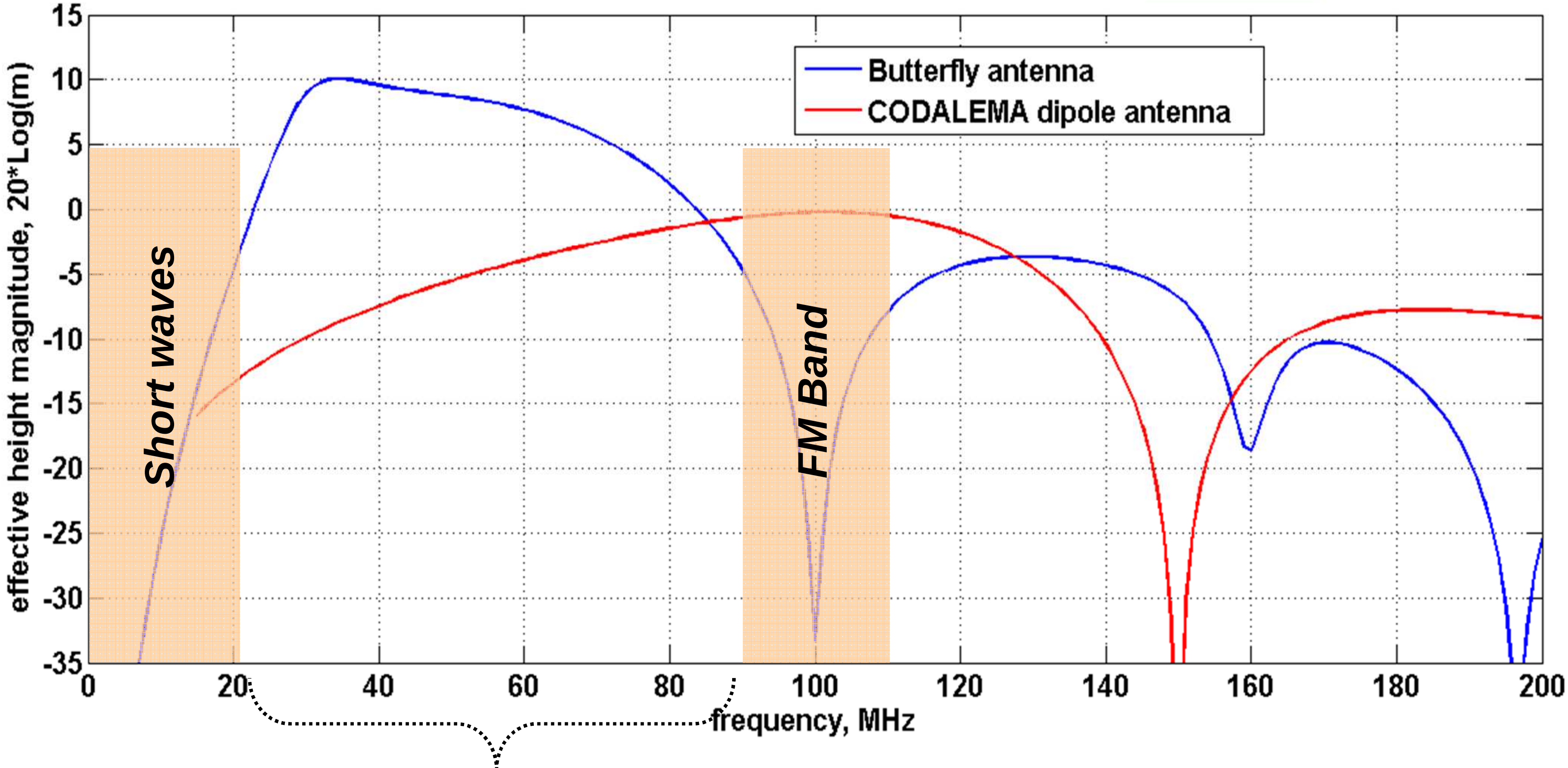


Input type	Differential
Input resistance	300Ω
Input reactance	6pF // 1uH
Voltage gain	A=26dB
1dB compression point	OCP=7dBm ICP=8.8mV on 300Ω
Out reflection coefficient	|S22|<-20dB [4-210MHz]
Power supply	6V to 15V by signal
Consumption	2 x 52mA, 625mW
Gain temperature drift	-0.026 dB/°C

Evolution from the CODALEMA active dipole to the Butterfly antenna

Didier Charrier

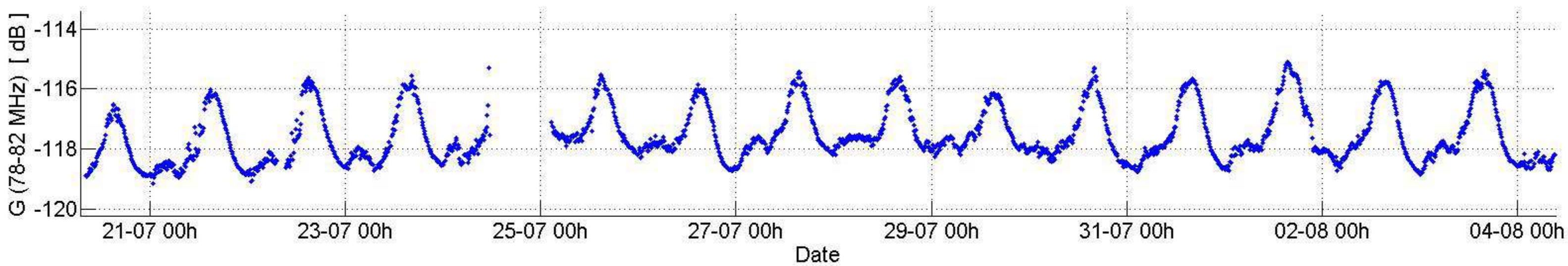
$20*Log_{10}(Abs(Vlna/E))$, for θ=0° (zenith)

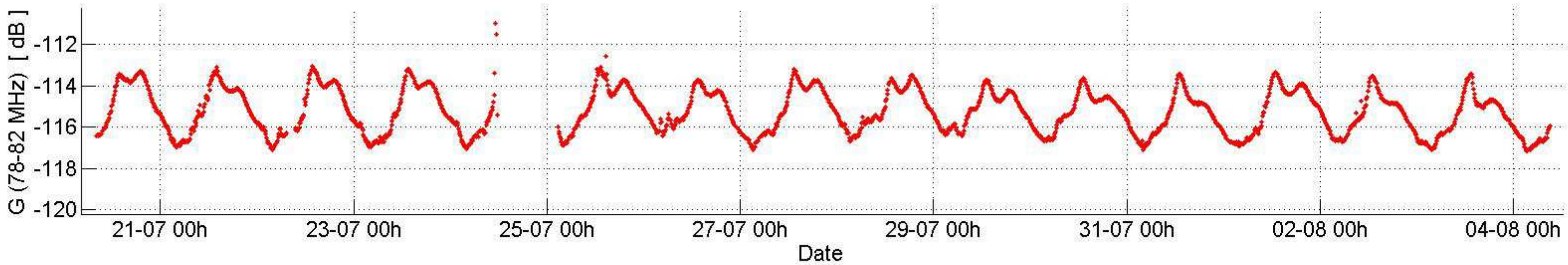


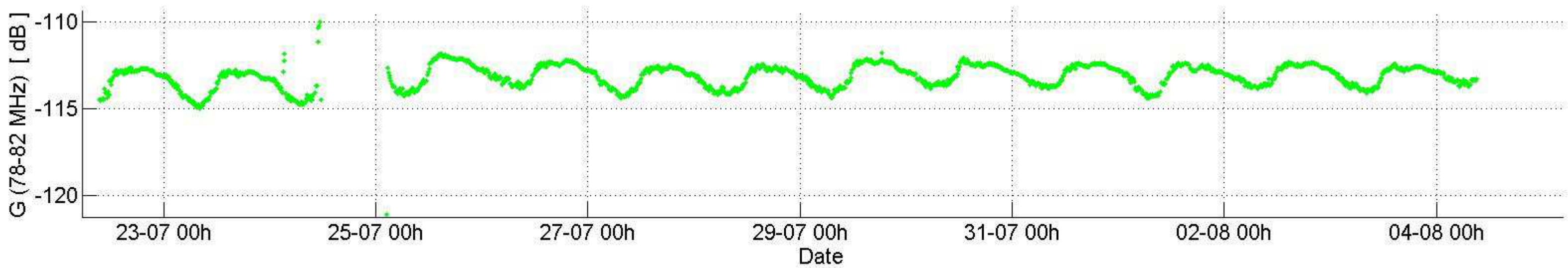
- The radio background can’t be used at DC-20MHz and 88-108MHz band
- Cosmic rays detection is supposed to be better with low frequencies

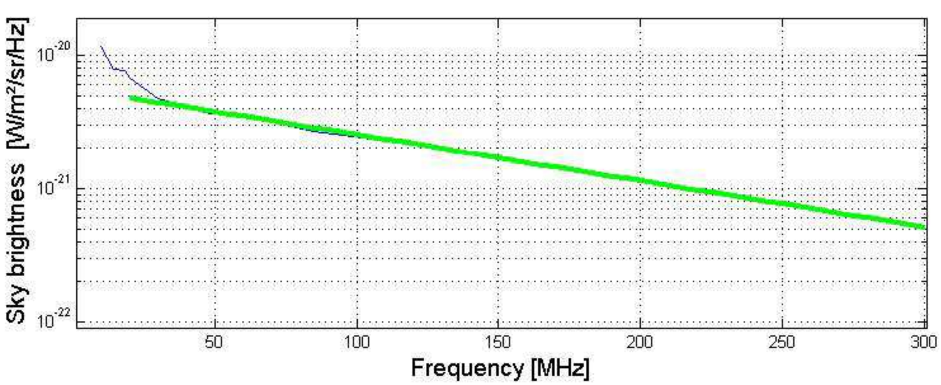
⇒Frequency range of the butterfly is maximized for the 25-90MHz band

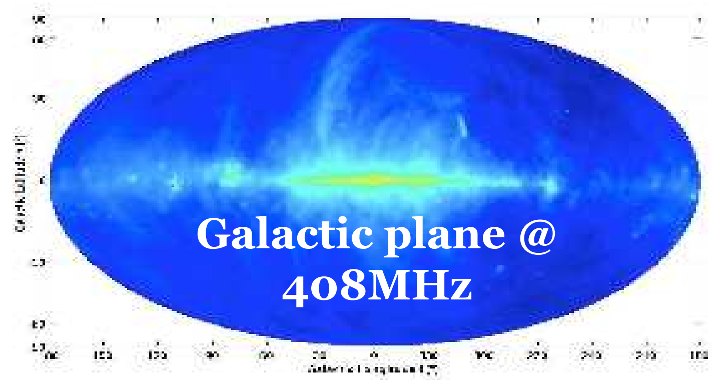
- Butterfly sensitivity is much better for this frequency range


G (78-82 MHz) [dB]
-114
-116
-118
-120
21-07 00h
23-07 00h
25-07 00h
27-07 00h
29-07 00h
31-07 00h
02-08 00h
04-08 00h
Date

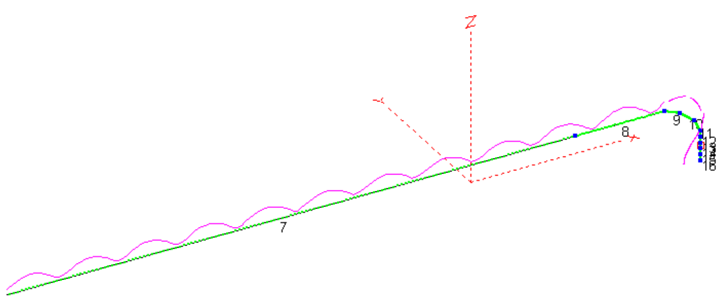

G (78-82 MHz) [dB]
-112
-114
-116
-118
-120
21-07 00h
23-07 00h
25-07 00h
27-07 00h
29-07 00h
31-07 00h
02-08 00h
04-08 00h
Date

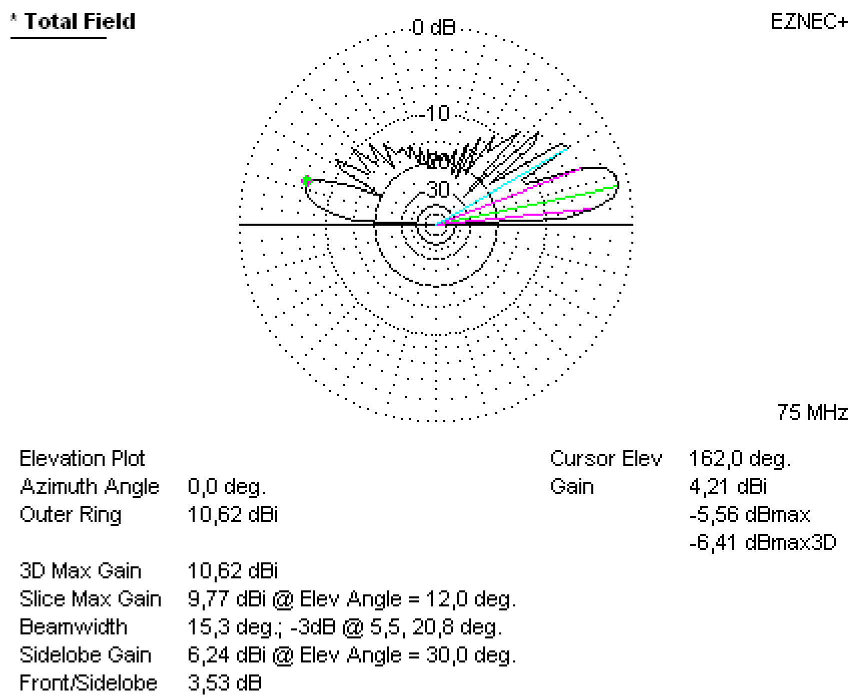

G (78-82 MHz) [dB]
-110
-115
-120
23-07 00h
25-07 00h
27-07 00h
29-07 00h
31-07 00h
02-08 00h
04-08 00h
Date


Sky brightness [W/m²/sr/Hz]
10^-20
10^-21
10^-22
50
100
150
200
250
300
Frequency [MHz]


Galactic plane @
408MHz

Beverage antennas





GRAND antennas

- Broadband & sensitive → active antennas (*a la* SUBATECH)
- Signal expected around horizon: limit lobe to few (~20?) degrees in zenith to improve signal/noise ratio & optimize threshold.

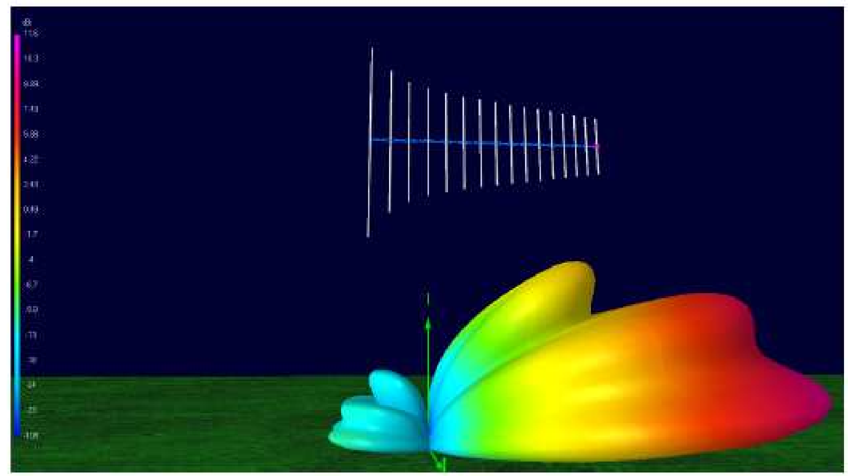
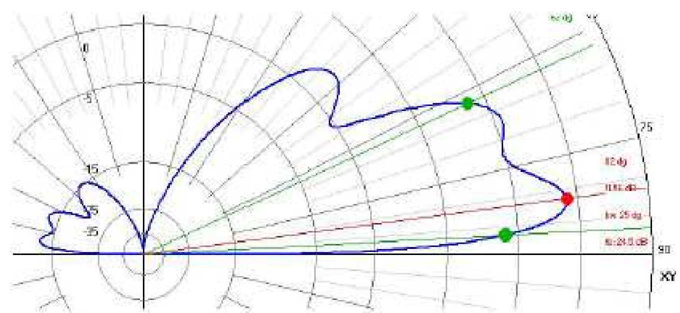


Figure 1 . Lobe 3D pour un sol réel à 150 MHz

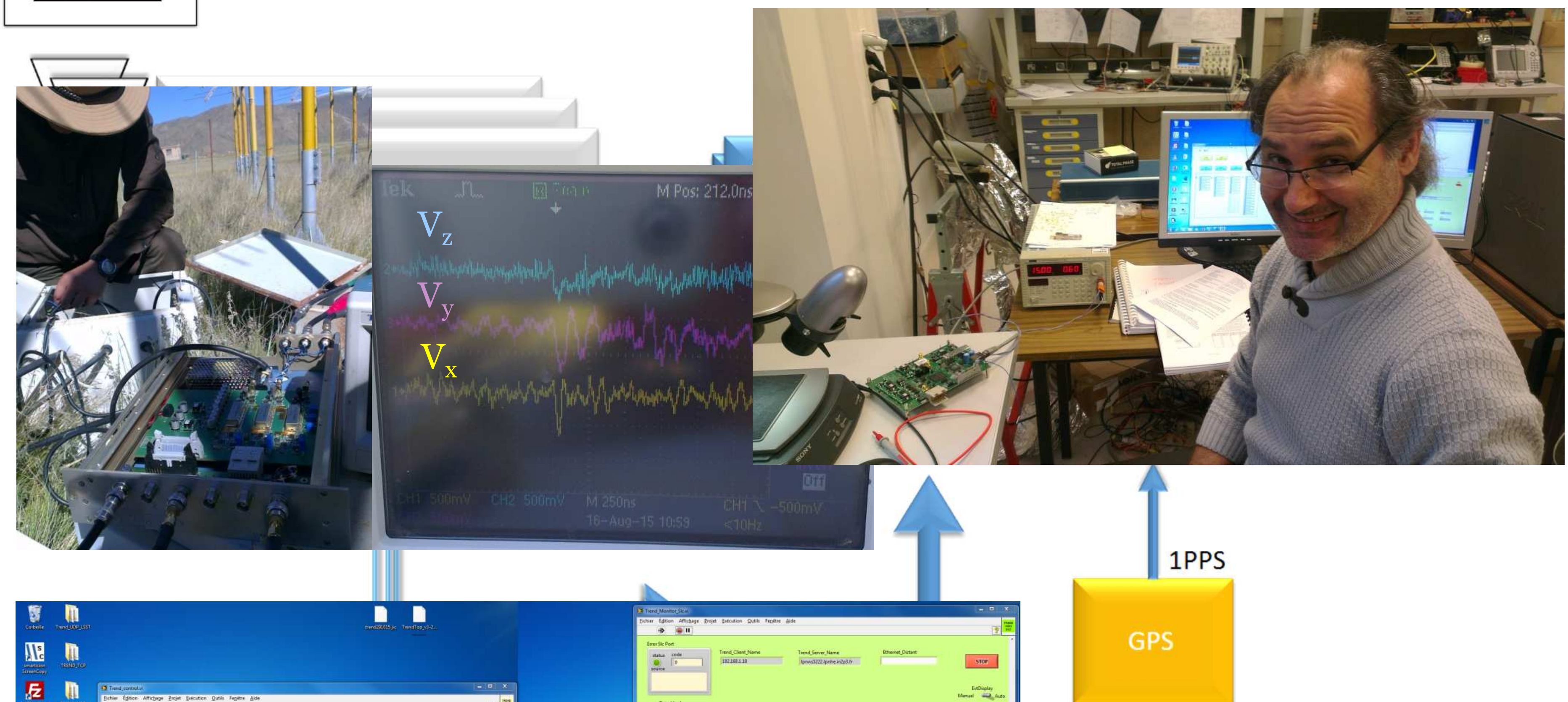


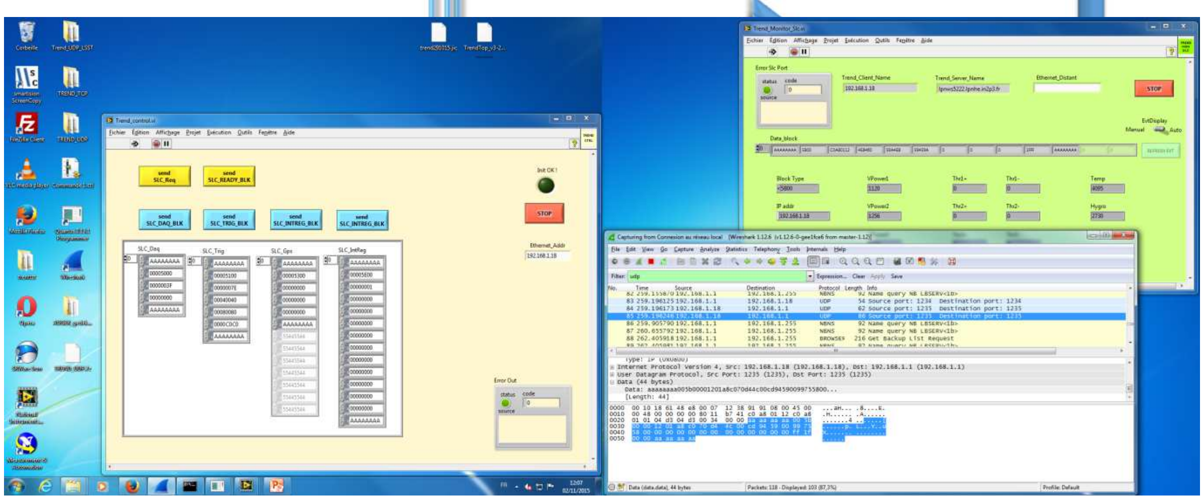
Budget for the detection unit

Element	Power consumption	Price
Antenna	-	10$
LNA	~500mW	<10$ x3
Filter	-	<20$ x3
Signal detection (shape selection & trigger)	negligeable	~10$x3
ADC+FPGA	~150mW	~50$
GPS	~100mW	<50$
Com.	~100mW	10$ or ?
Power generator: solar pannel (or wind mill?)	-	~50$
Mechanics	-	100$
Cables, connectors & PCB	-	100$
Total	**~ 1W**	**490$**

Should remain below 2W & ~500$/unit.

GRANDproto FE electronics





- Analog card: noise level @ nominal perfs + signals observed onsite.
- Numerical card tests under way since November.