(pre)proposal for a Giant Radio Array for Neutrino Detection

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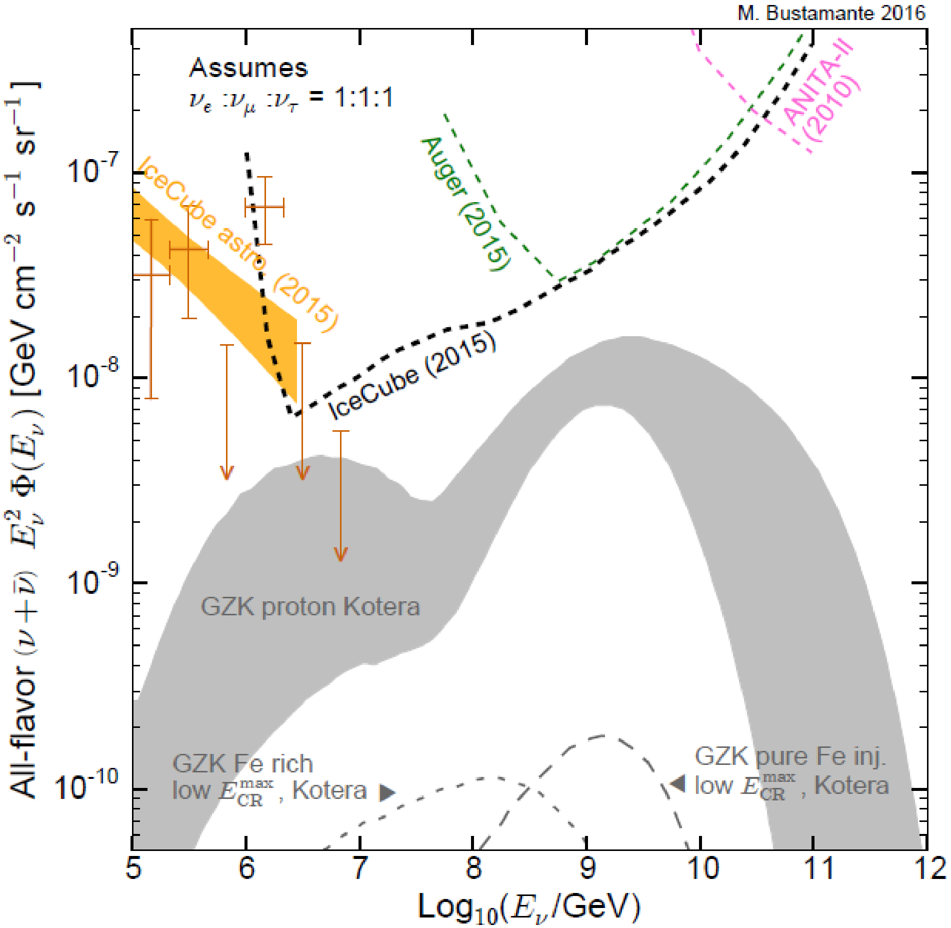
GRAND science case: cosmogenic neutrinos

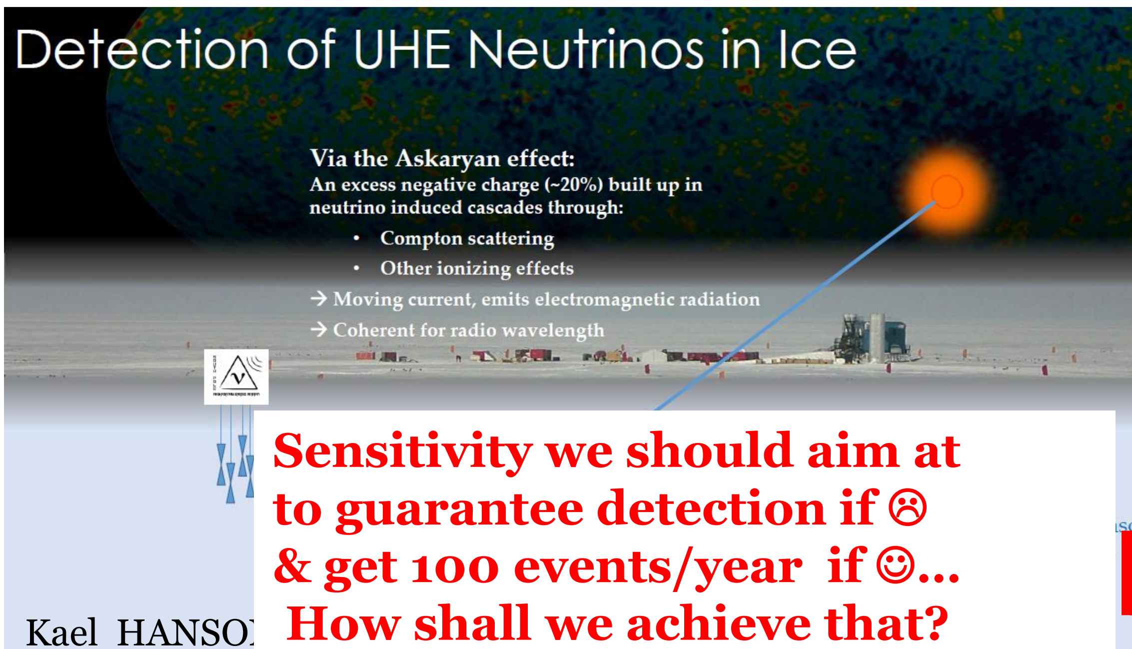
$$UHECR_{E>10^{19.5}eV} + \gamma_{CMB} \rightarrow \ \ldots \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e$$

- Why are they worth looking for?
  - Sensitive to the UHECR composition (fewer's if nuclei)
  - Probe the high-redshift UHECR sources evolution
  - Probe neutrino properties at previously unexplored energies
  - (Because they are out there)

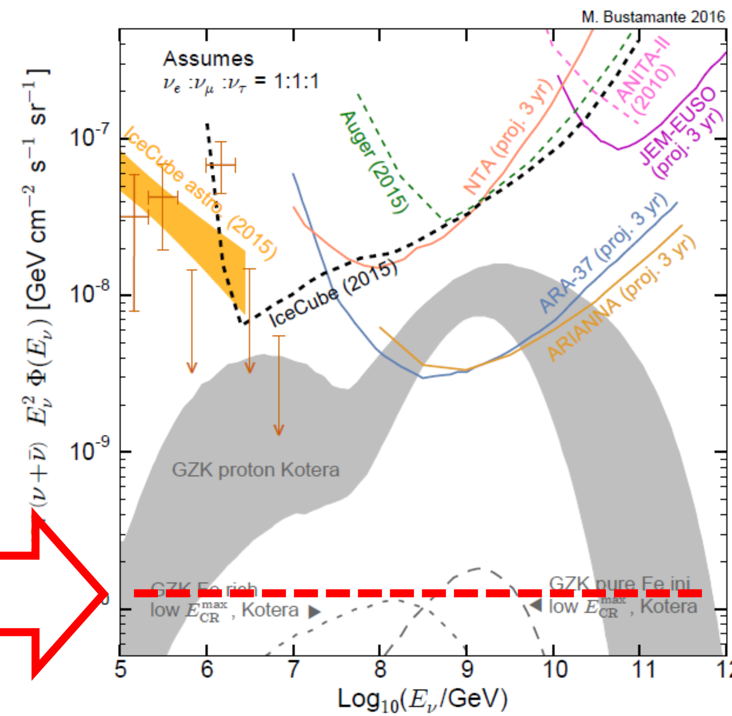


EeV neutrino detection

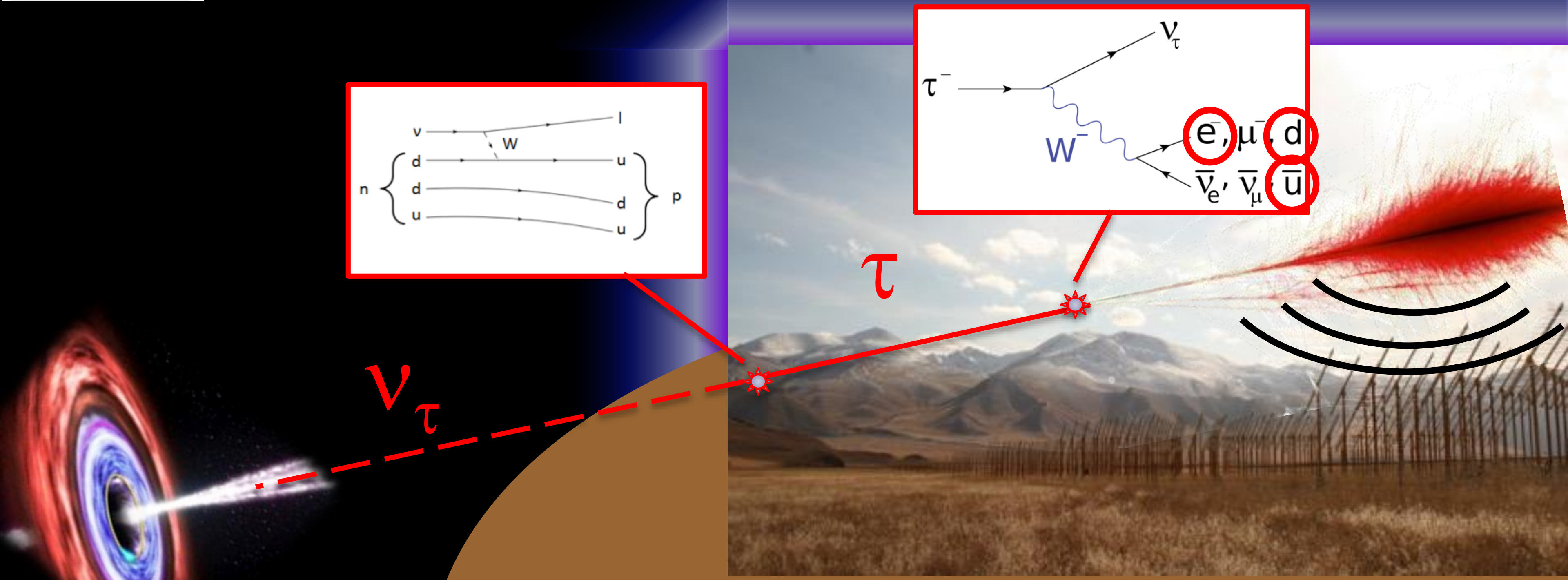
- Challenge: how to gain order(s) of magnitude in sensitivity?
- Go for a BIG detector. One (popular) option: radio in Antarctica (ANITA, ARA & ARIANA)
  - Principle: in-ice interaction → shower → radio emission
  - ☺ Antarctica: large target volume + ice transparency + low background
  - ☹ Antarctica: complicated access & environment, expensive.



Sensitivity we should aim at to guarantee detection if ☹ & get 100 events/year if ☺… How shall we achieve that?



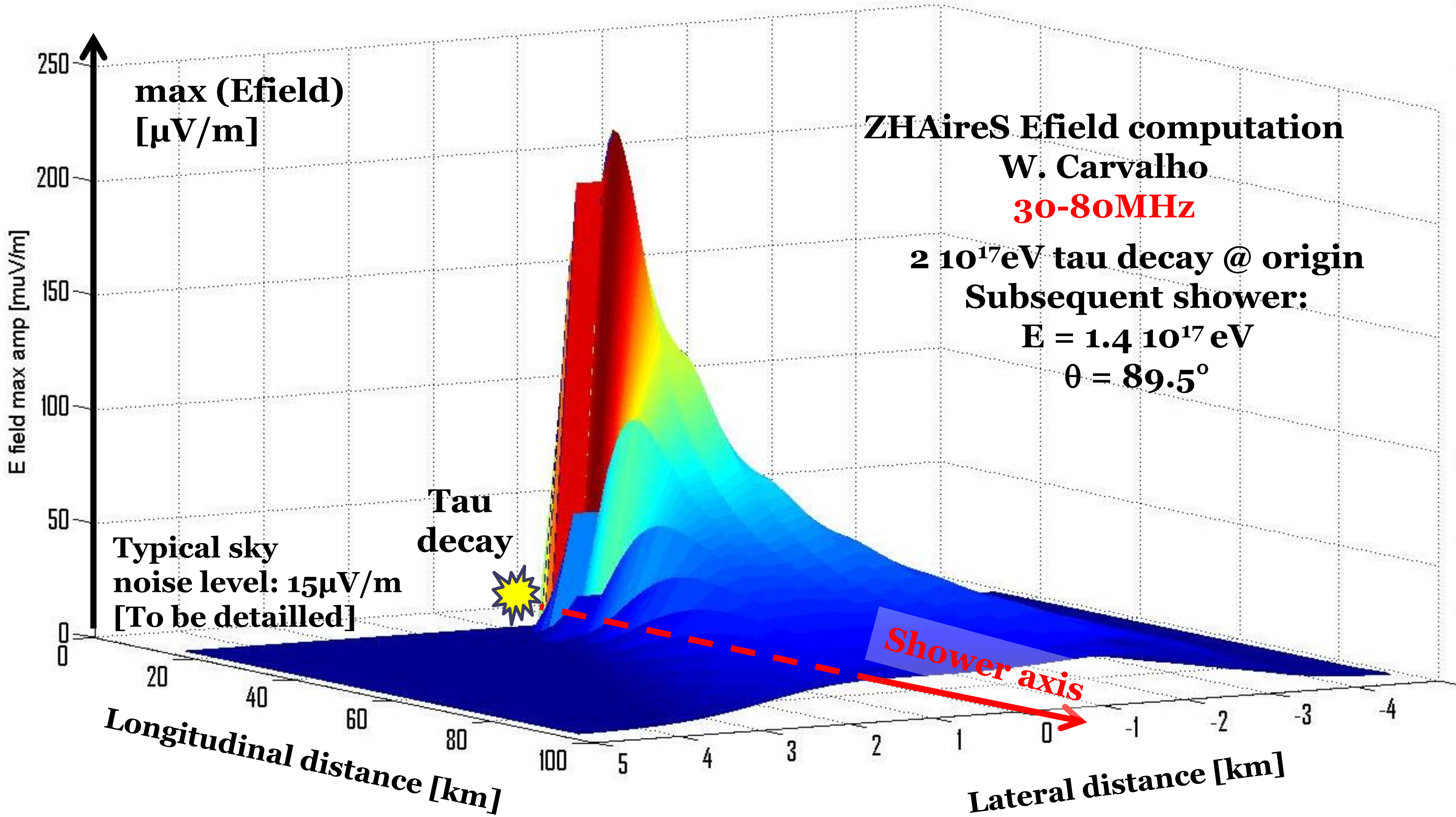
EeV neutrino detection



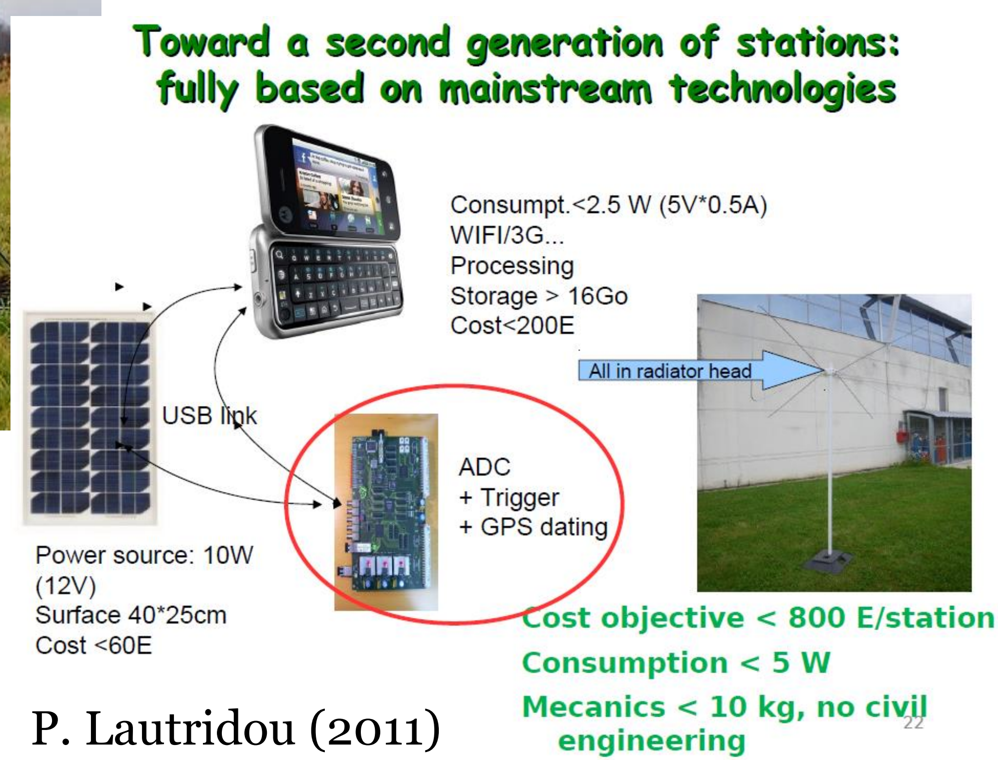
Rock target:

- Principle:
  - ν-induced tau decays in atmosphere generate ~horizontal extensive air showers.
    [Fargion astro-ph/99066450, Bertou astro-ph/0104452]
- Issues:
  - VERY seldom events
  - Earth-skimming trajectories

(Very) inclined EAS radio emission



A cheap EAS radio detection unit?

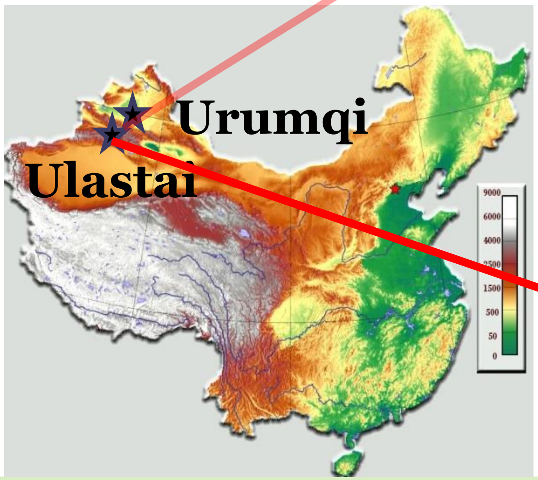


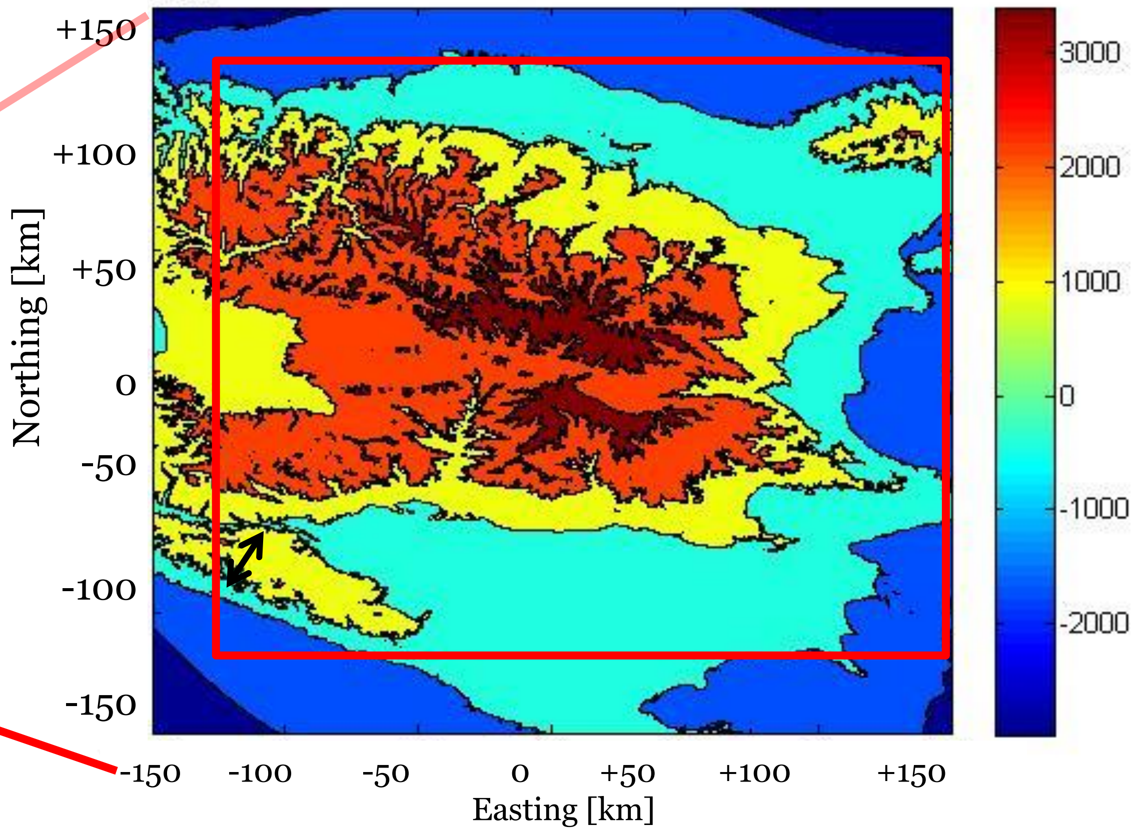
P. Lautridou (2011)


a GIANT array may be technically & financialy feasable!
... How well would it perform?

GRAND ν sensitivity study - Setup

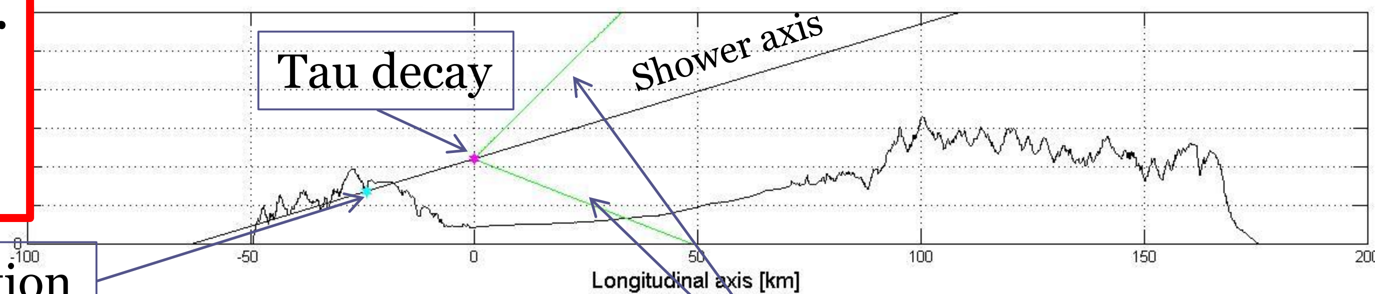
- Simulation layout of 90'000 antennas over **60'000km²** (800m step size square grid)
- MC down to τ decay (E_ν in 10^{17} - 10^{21} eV, θ in [85-95°])
- Shower radio emission:
  - Not yet validated for very inclined showers
  - (Very) time consuming
- Preliminar study with **radio signal parametrization** (trigger volume = cone with shape = f(E) determined through ZHAireS simulations) .





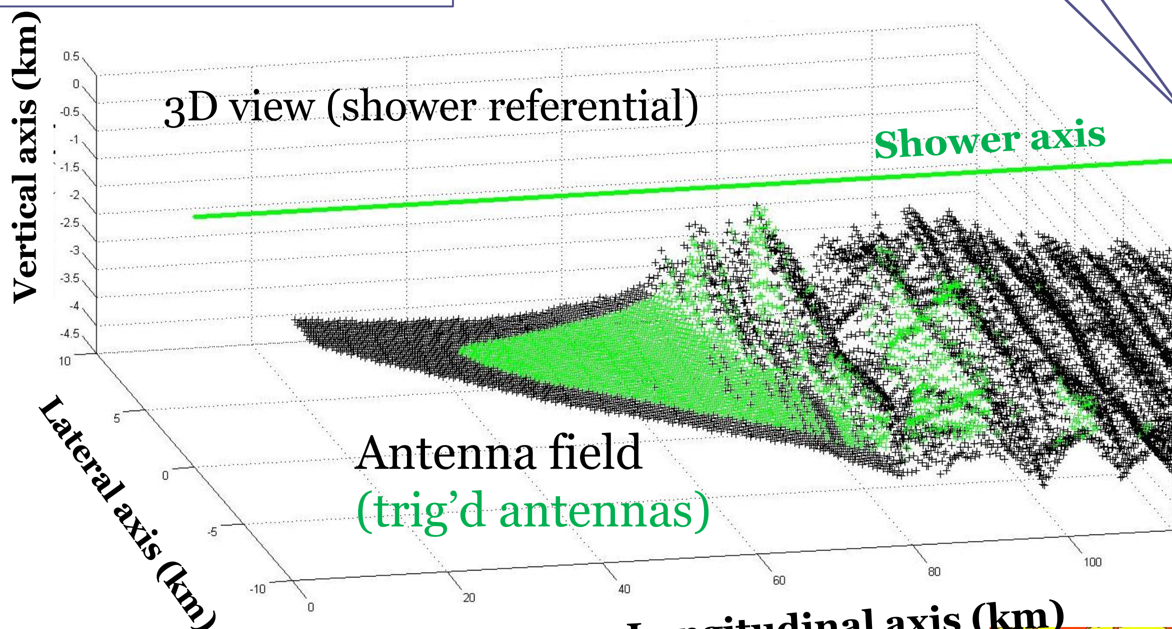
3 10^{20}eV neutrino
2.4 10^{20}eV shower
θ = 88°
2114 antennas triggered

Cut view (Earth referential)

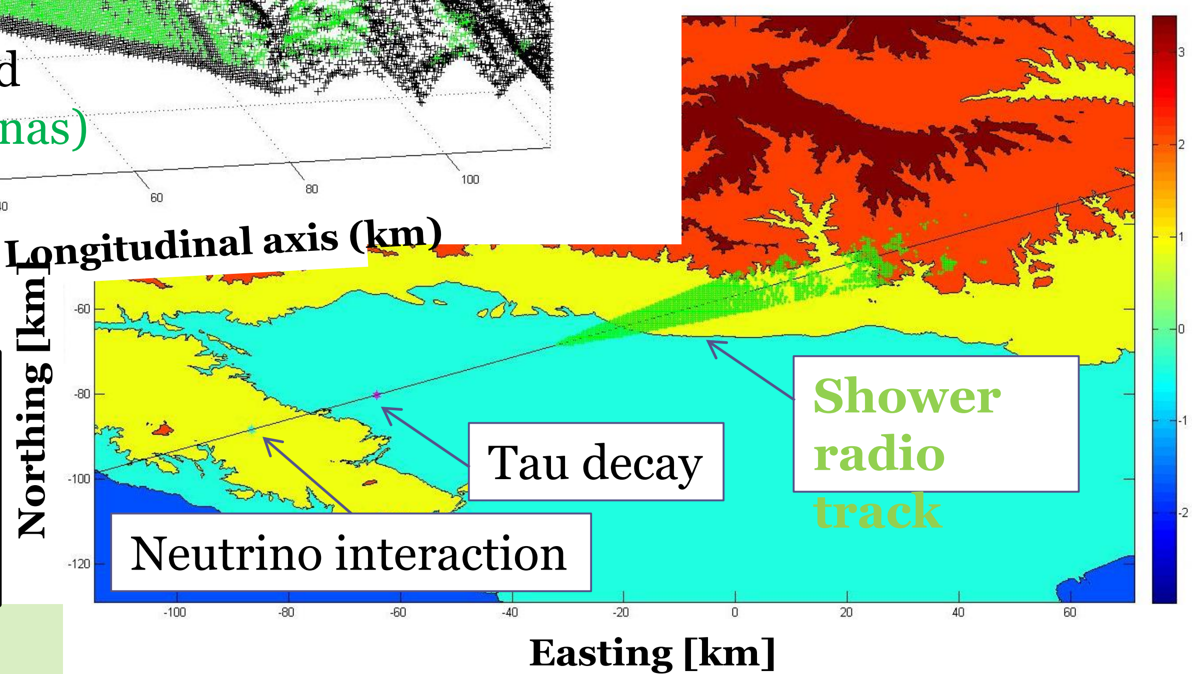


Radio emission cone
(4.5° for E>30μV/m @ E_{sh} = 2.4 10^{20} eV)

3D view (shower referential)

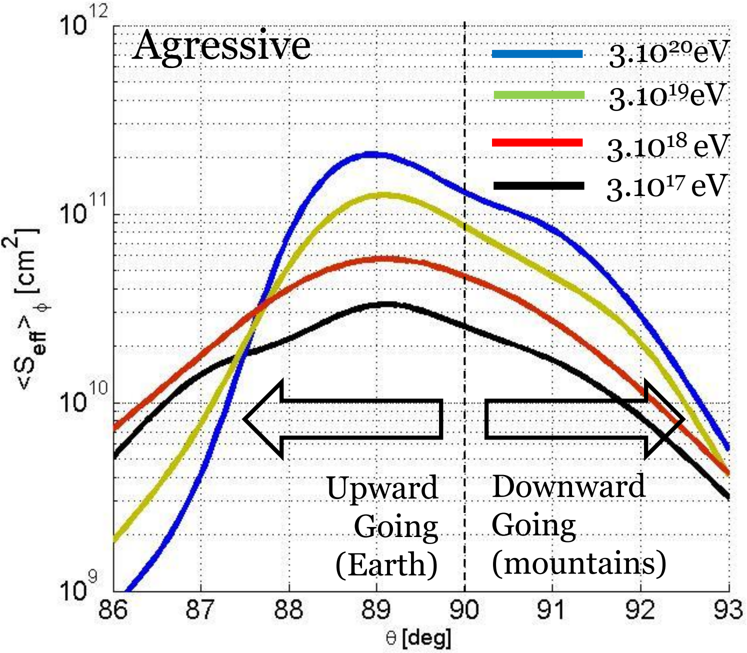


Top view (Earth referential)

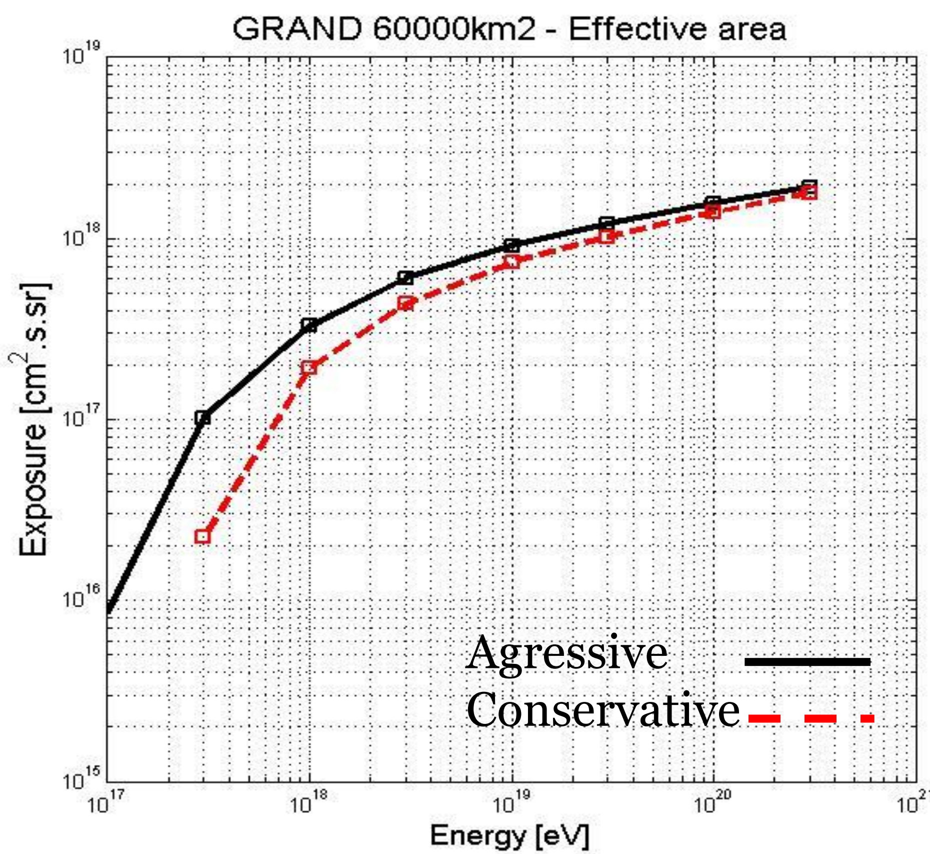


Shower tagged as « detected » if a cluster of 8+ antennas is inside the radio detection cone.

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



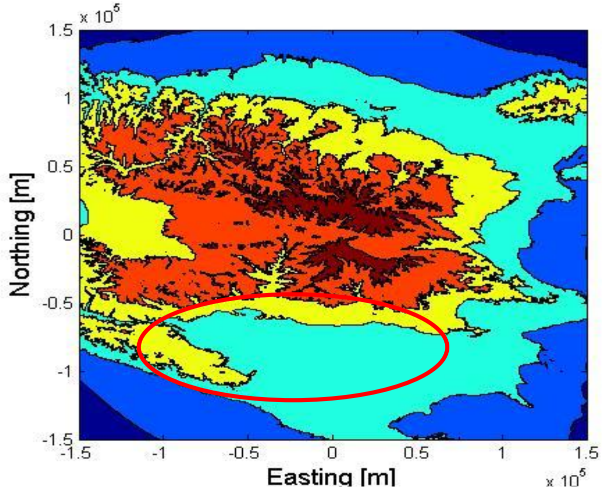
- 60'000km² simulation setup
- single flavor flux $\phi(E)= \phi_0 E^{-2}$
- no candidate in 3 years

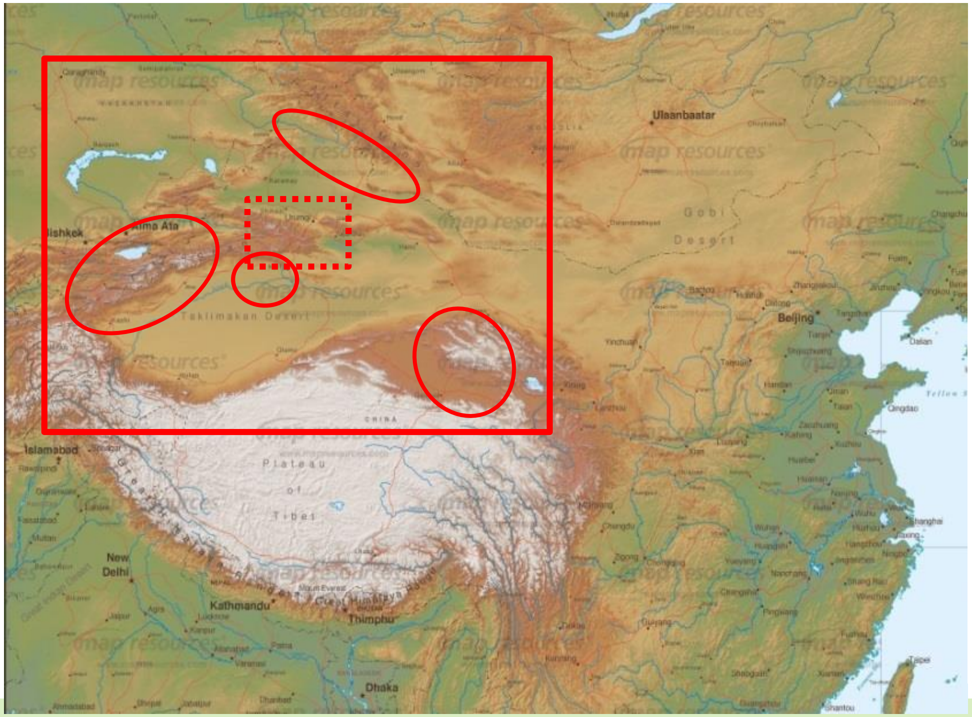
⇨ 90% CL integral limit:

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

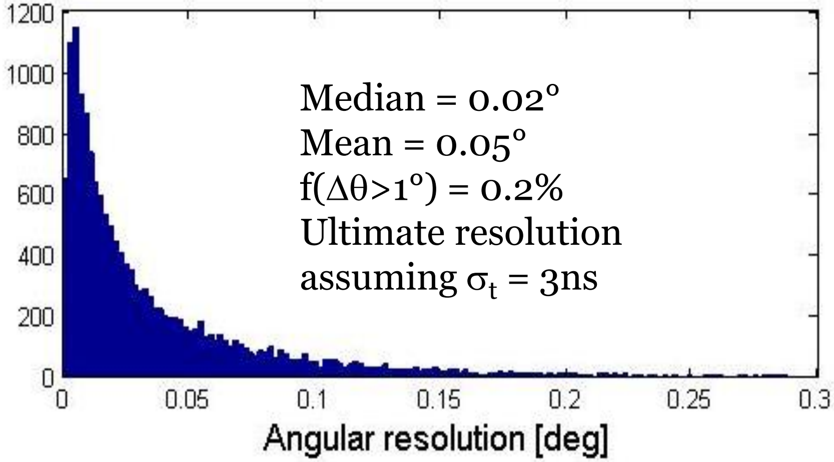
GRAND ν sensitivity study

- Target sensitivity: $\phi_0 = 5\ 10^{-11}$ GeV/cm²/sr/s (~10 times better than 60000km² simu result)
- **Driver: go for hotspots!** Then 200000km² may be enough to reach target sensitivity
- Giant simulation area (1'000'000 antennas over 1'000'000 km²?) to identify hotspots (using « generic » showers)
- On-going work (K. De Vries & W. Carvalho)



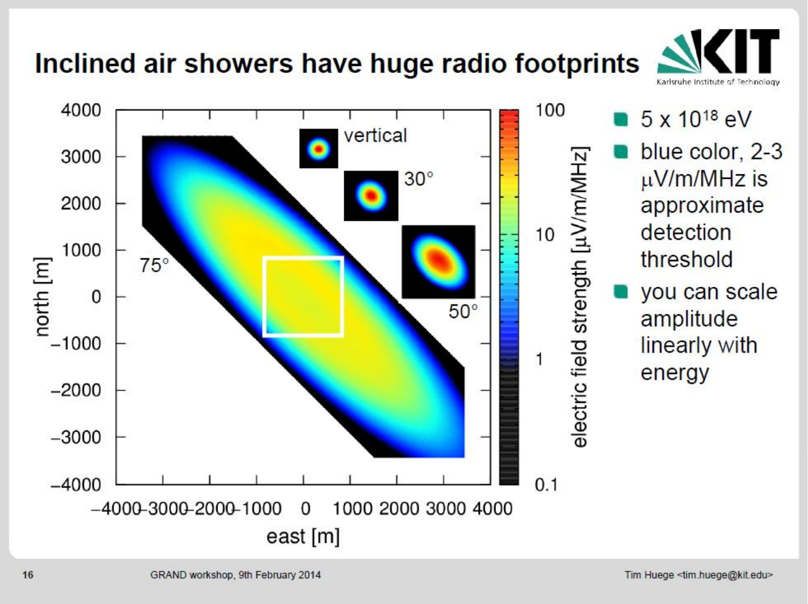


Atop of that: (potentially) great angular resolution … thanks to mountains.

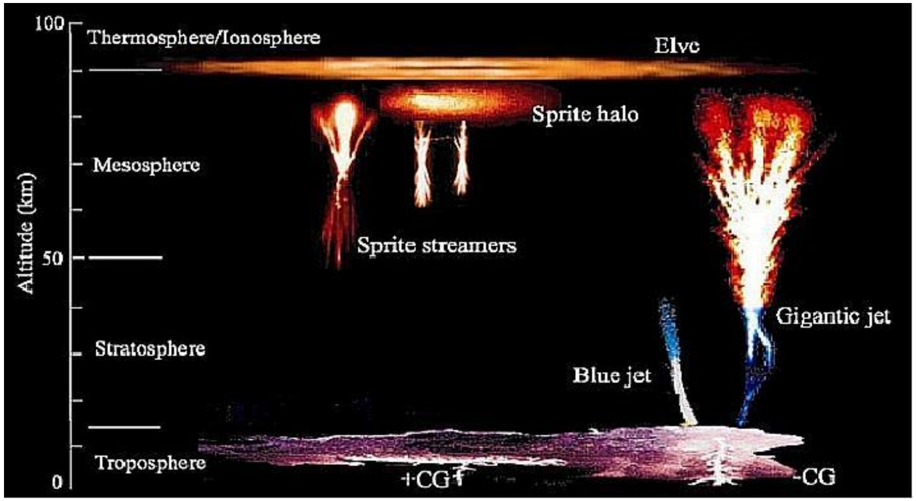


Other science cases for GRAND

- **Trans-GZK UHECRs:** significant stat achievable above 10^{19}eV thanks to huge effective area AUGER x 10 (?)...



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

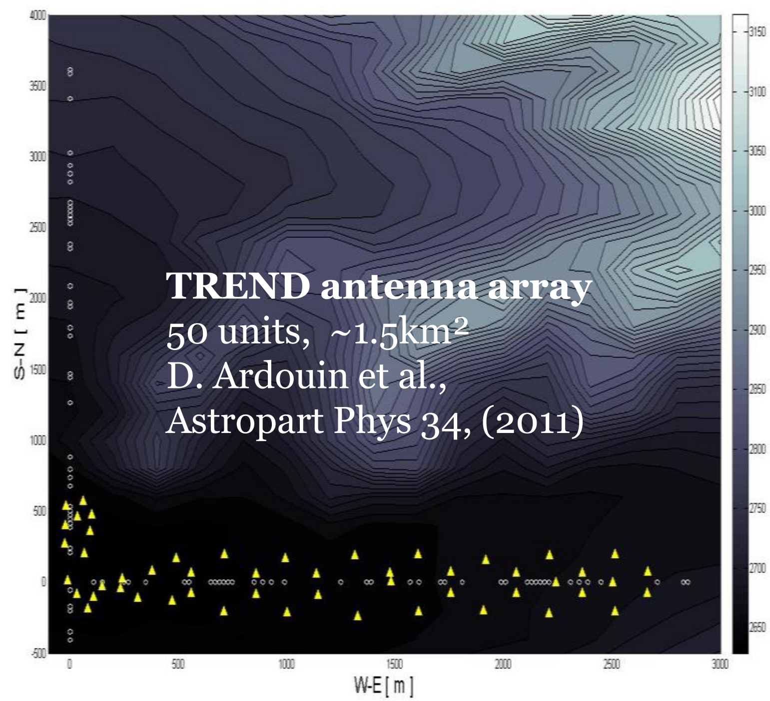


GRAND challenges

- Autonomous radiodetection of ~horizontal showers?
- Background rejection / event identification
- Technological challenges: trigger, data collection, maintenance, ...

The TREND project (2008-2014)

- TREND proposed in 2008 with Wu Xiang Ping (NAOC), P. Lautridou & D. Ardouin (Nantes)
- 1st goal: **autonomous EAS radio detection & identification**. Site: 21CMA radio-interferometer (Ulastai, XinJiang province).
- **Economic setup**: 50 independant monopolar antennas, transfert of analog signal to DAQ room, on-the-fly digitization, soft trigger (th = 8xσ_{noise}). DAQ ~100% duty cycle up to 200Hz trigger / antenna.
- **Small team**: NAOC (Wu XiangPing + 2), IHEP (1), OM (@Beijing, 2009-2013) & V. Niess

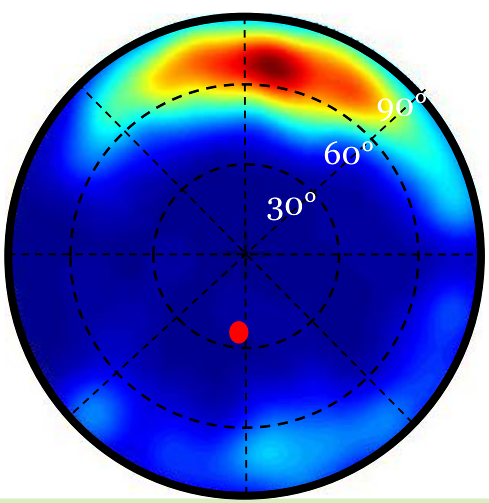


TREND-50 results

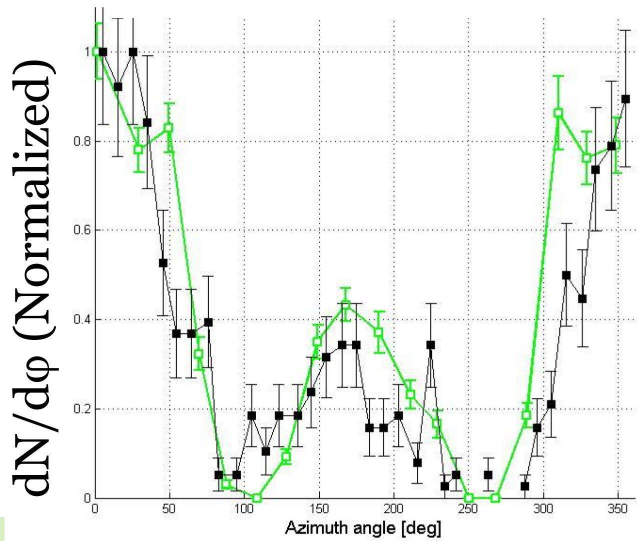
- Off-line selection of EAS candidates based on specific criteria (wavefront, trigger pattern at ground, direction & time correlation…)
- 465 EAS candidates selected in 317 live days. **Direction distribution similar to simulated EAS.**

⇨ **TREND goal reached:** autonomous EAS detection & identification with radio antennas is possible

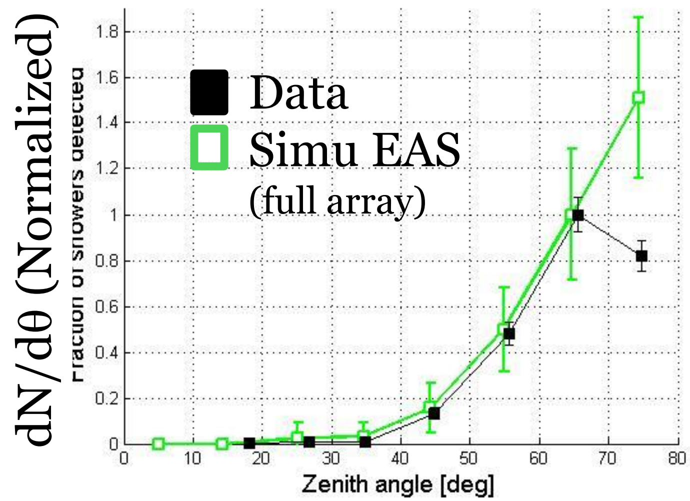
⇨ Issue: limited efficiency (<10% if threshold @ 10^{17}eV).
DAQ duty cycle + selection cuts? [Work in progress]



Azimuthal distribution

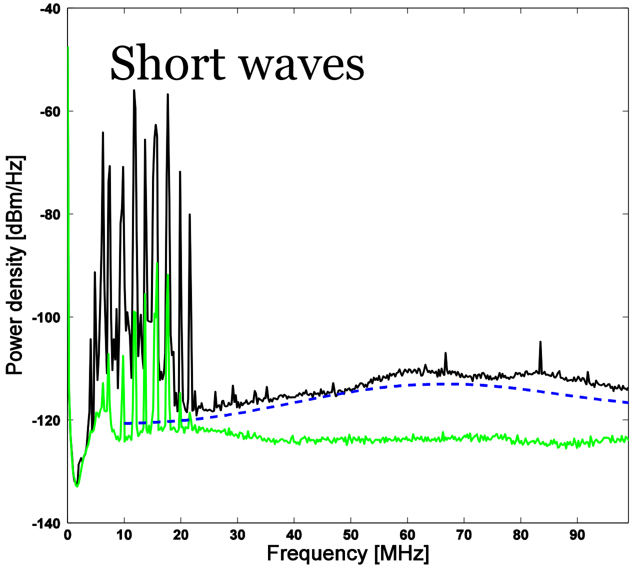


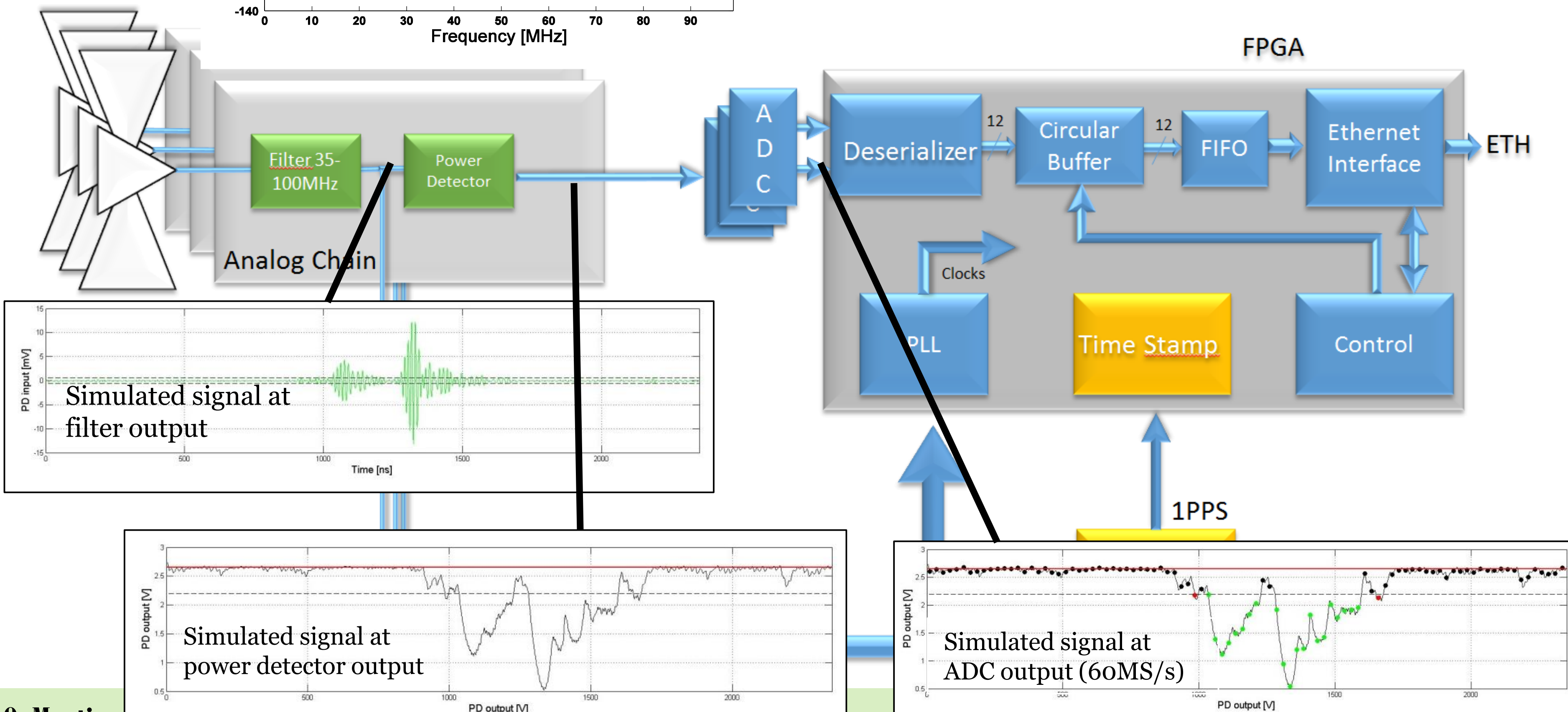
Zenithal distribution



…oto array (2014-…)

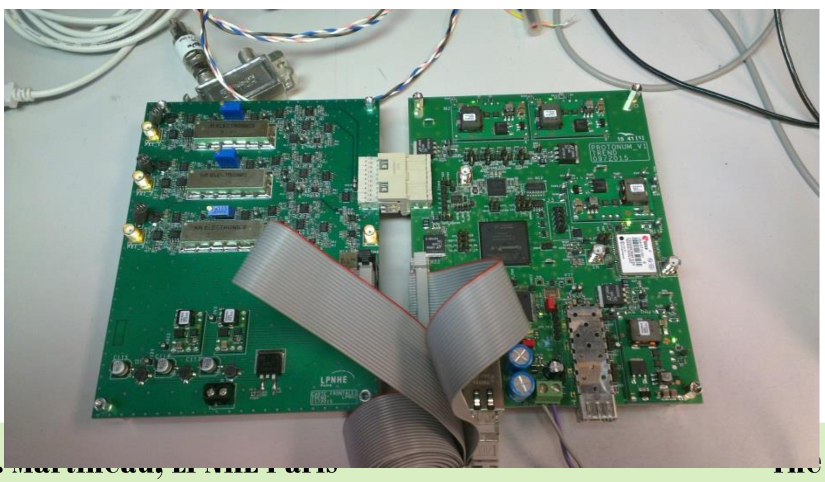
- Hybri… …ntennas + 21 scintillators.
- Princ… …es & use scintillator data as a cross check
  ➔ det… …cy.
- DAQ … …, French company prod) designed for **100%**
  duty

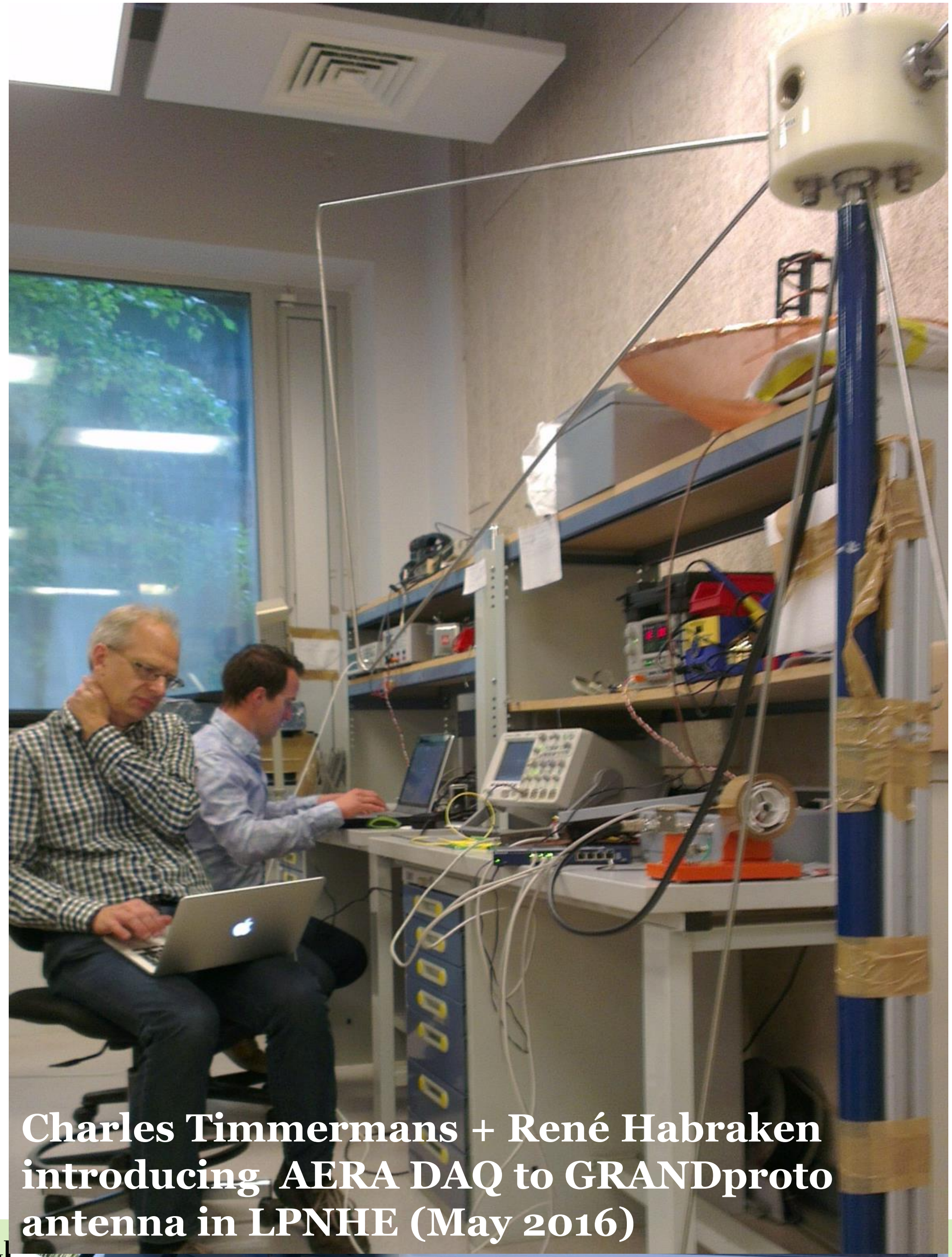




GRANDproto

- 6 antennas + 6 scintillators deployed summer 2015 for tests.
- Radio DAQ card tested on site in April 2016. Full deployment expected before end 2016.
- Sandra Le Coz (Auger-Easier PhD) in NAOC for 2 years since October 2015 (CAS fellowship).
- **3 units of AUGER-AERA Nijmegen DAQ to be deployed on site in summer 2016.**





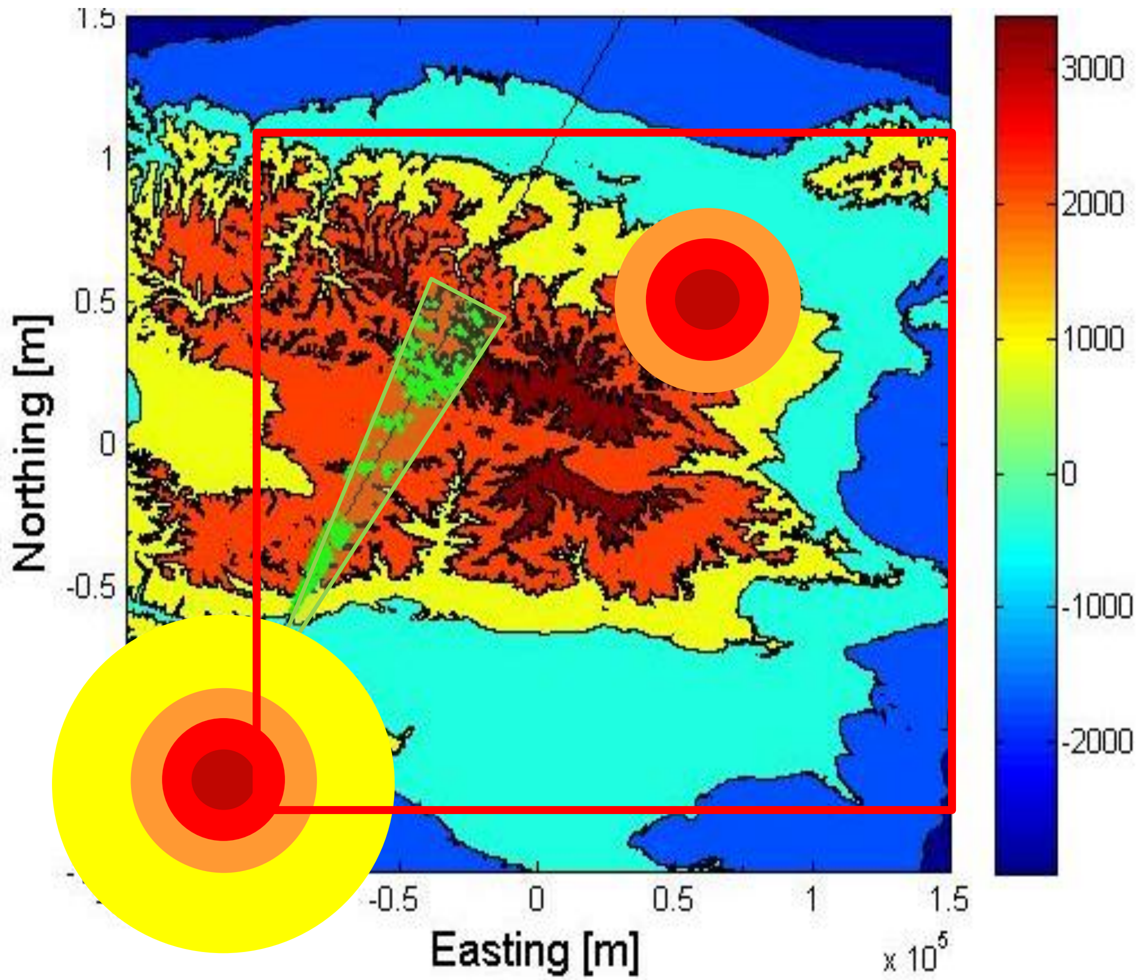
Charles Timmermans + René Habraken introducing AERA DAQ to GRANDproto antenna in LPNHE (May 2016)

GRAND trigger & data transfer

- Estimation of expected coinc rate:
  - Coinc rate between 6 antennas from TREND setup with 800m spacing: 1 event in 52 live days.
  - Scaling: **~2500 events/day in GRAND**
- Possible strategies:
  - L2 trigger: validate antenna triggers only if coincs with neighbouring (<1km) antennas. More complex but kills trig rate.
  - Minimal data: save very few info (amplitude & trig time) and transfer all for each antenna L1 trigger. Cheap & easy… but dangerous & limited.
  - Cluster station: group 3 antennas (<100m) and perform direction recons to filter out (most) background. More costy (Nants x 3) but better data quality.
- **Probably too early to be too specific at this stage. Loads of (exciting) work ahead, but solutions surely exist.**

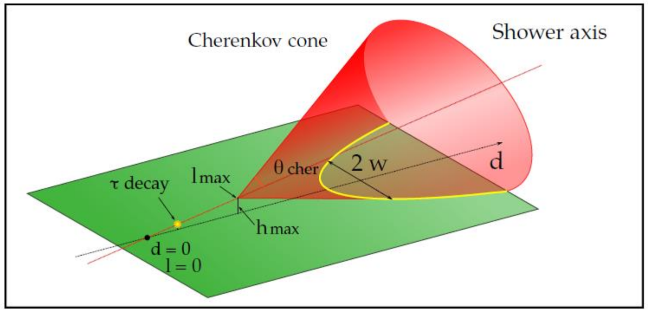
GRAND background discrimination

- GRAND estimation (scalled TREND event rate): ~10^6 background event/year.
- Trigger pattern @ ground + wavefront + direction reconstruction provide VERY POWEFULL means of discrimination
- Clustering analysis in ANITA: 5 candidates survive out of 270000 reconstructed events…

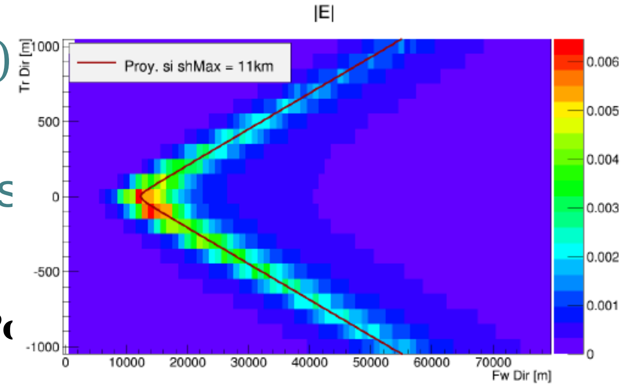


Terrestrial background rejection

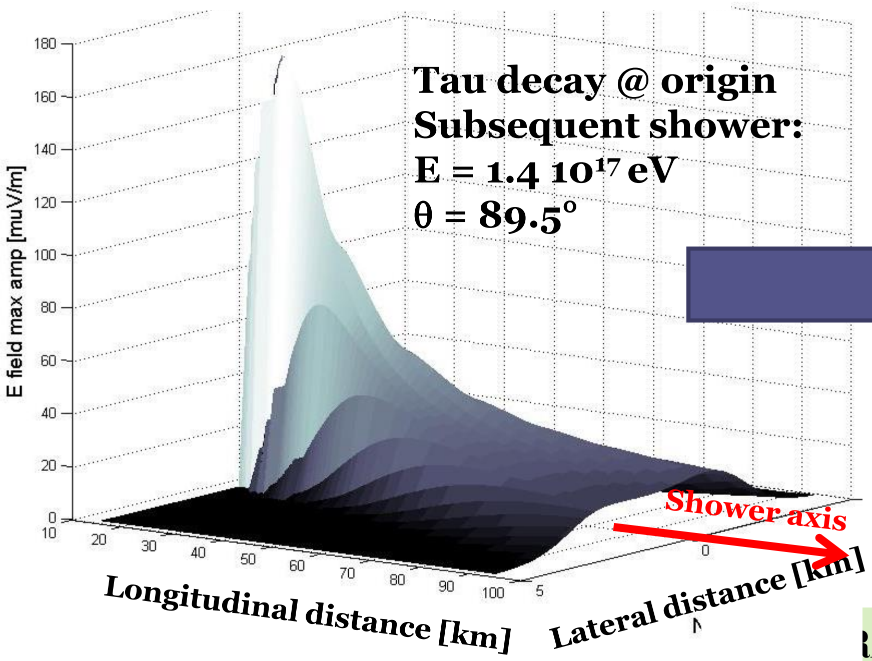
W Carvalho @ GRAND workshop

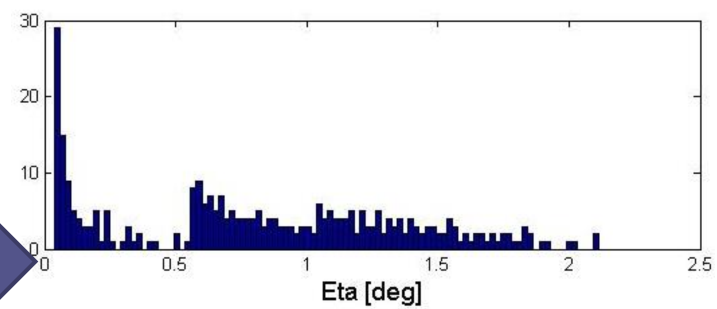


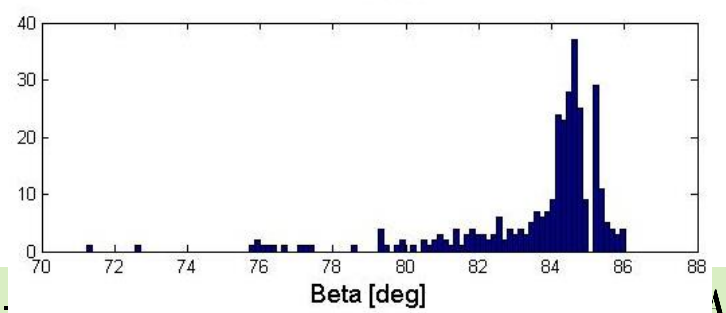
- EAS signatures
  - Trigger pattern at ground (beamed emission with flat wavefront & lateral drop)
  - Cerenkov cone
  - Polarization : $\perp B_{geo}$ & $\perp v$ at 1st order on all antennas



30-80MHz Efield computation
ZHAireS simulation code







Timeline & budget

- Goal: <500$/antenna ➔ 100M$ project budget range
- Timeline impossible to define today. Possible steps:
  - GRANDproto (2017-2020 (?)): establish efficient automous radio detection + R&D for autonomous stations with optimized sensitivity to inclined showers
  - GRAND engineering array: several 100s to few 1000 antennas: validate very inclined shower detection, trigger & data transfer. UHECRs detection.
  - First GRAND hotspot: full scale deployment (few 10000) on one hotspot for final validation. Begin neutrino search.
  - Full setup (200'000): could very well be in different sites in the world.

GRAND people

- GRAND study initiated (2012-2014) with very limited ressources (OM+ V. Niess for ν sensitivity study, K. Kotera for science case)
- Seminal GRAND workshop @ LPNHE (February 2015)
  - 38 participants (AUGER, IceCube, ANITA, ARA, …) ➔ ICRC paper
- 2nd GRAND workshop at KICP Chicago (December 2015)
- Presentations at ICRC2015, VLVNT2015, VEHPA2016 and other workshops.
- Obvious interest, individuals getting involved… at various rate! ➔ Slow progress…
- **Join us!**


GRAND workshop, LPNHE, Feb 9-11, 2015

PoS PROCEEDINGS OF SCIENCE

The Giant Radio Array for Neutrino Detection

Olivier Martineau-Huynh[1], Kumiko Kotera[2], Didier Charrier[3], Sijbrand De Jong[4], Krijn D. de Vries[5], Ke Fang[6], Zhaoyang Feng[7], Chad Finley[8], Quanbu Gou[7], Junhua Gu[9], Hongbo Hu[7], Kohta Murase[10], Valentin Niess[11], Foteini Oikonomou[10], Nicolas Renault-Tinacci[9], Julia Schmid[12], Charles Timmermans[*,3], Zhen Wang[7], Xiangping Wu[9], Jianli Zhang[9], Yi Zhang[9]

Take-home message

- GRAND proposal desig… a EeV neutrino discovery instrument … scenario) and a precision* instrume… enario).

  *: large stat… degree resolution.
- Probably takes 200’… 00’000 antennas to reach that goa…
- Loads of exc…
  - White pap… chievable perfs (based on … tatus).
  - Optimise … detection efficiency.
  - … owers
  - …es … .
  - S… pa… je… l)

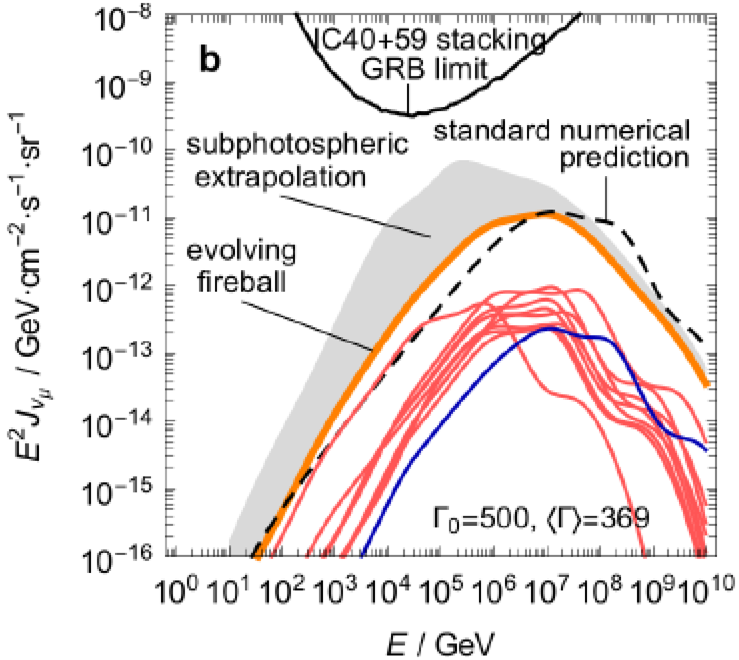
GRB prompt vs. afterglow neutrinos

Prompt neutrinos

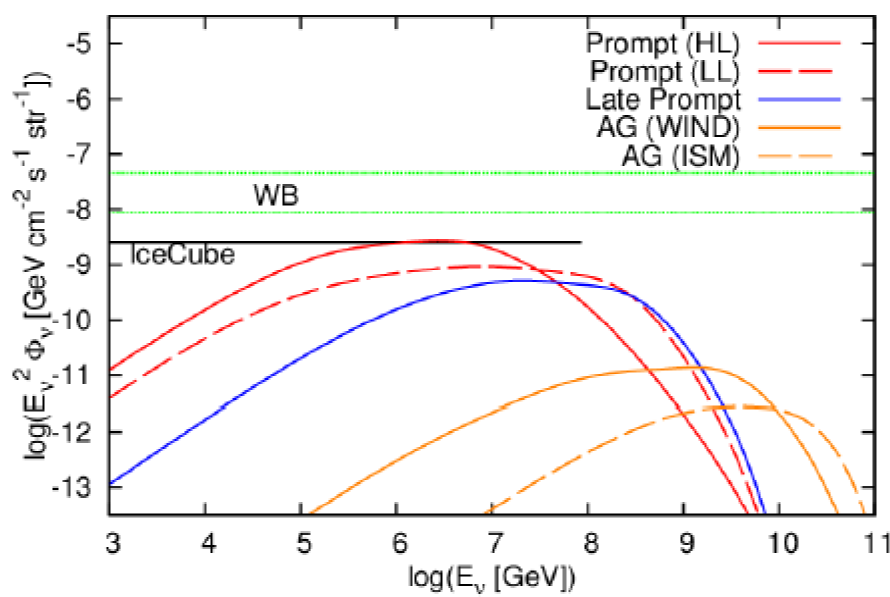
- Modeled via $p\gamma$ in internal in-jet collisions
- Flux peaks at $\sim$ PeV
- Use IceCube, ANTARES, KM3NeT

Afterglow neutrinos

- Modeled via $p\gamma$ in jet-medium collisions
- Flux peaks at $\sim$ EeV
- Use ARA, ARIANNA, ANITA, GRAND

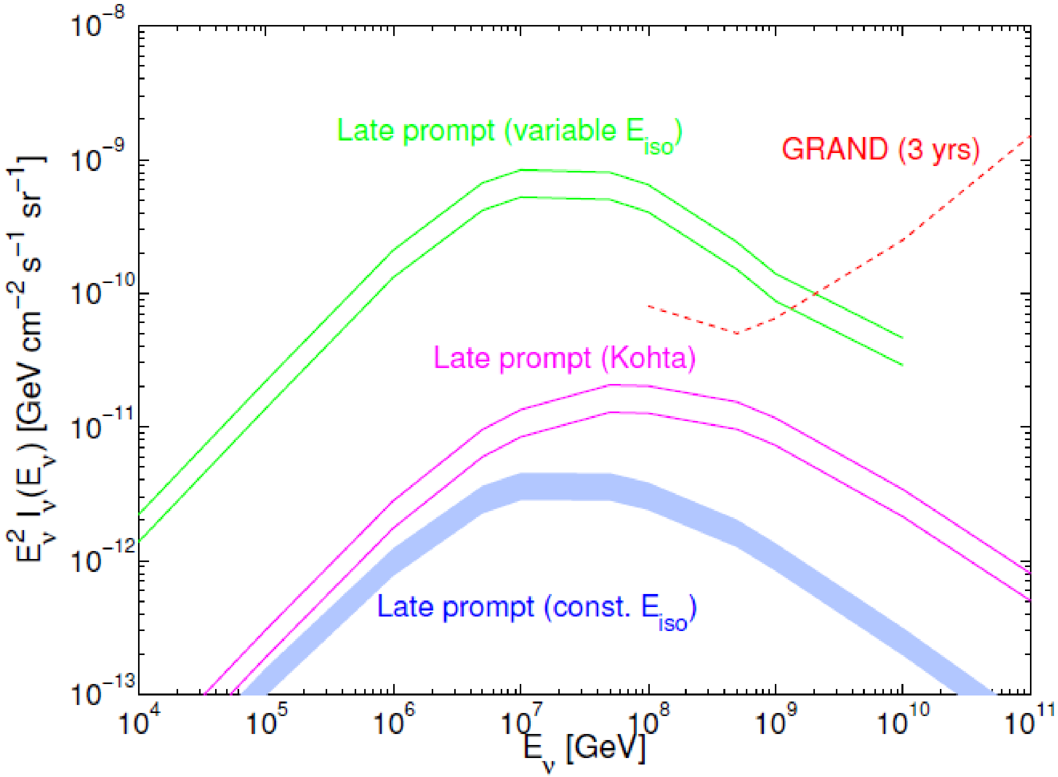


[MB, K. MURASE *et al.*, *Nat. Comm.* **6**, 6783 (2015) [1409.2874]]



[K. MURASE, *PRD* **76**, 123001 (2007) [0707.1140]]

Updated late prompt predictions



- Variable E_{iso}: Energy emitted $\propto$ afterglow luminosity

  $\lesssim$ 10 events in 3 yr of GRAND

- Late prompt (Kohta): MURASE 2007 with different parameters

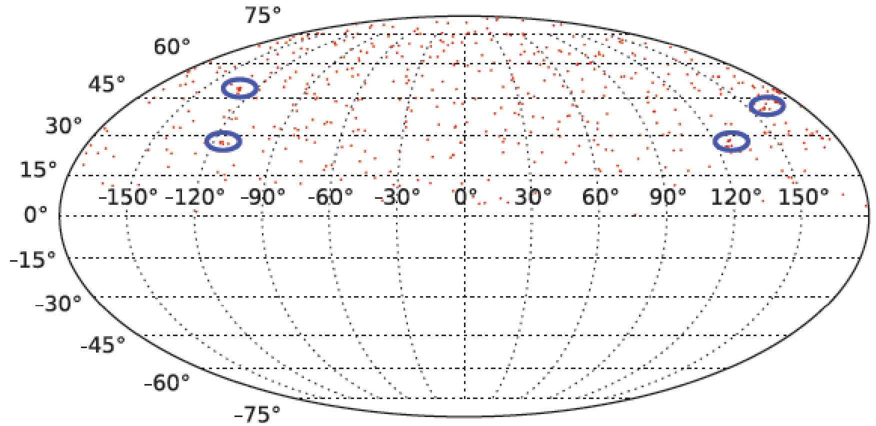
  $\sim$ 1 event

- Constant E_{iso}: Fixed 10^{50} erg (source frame)

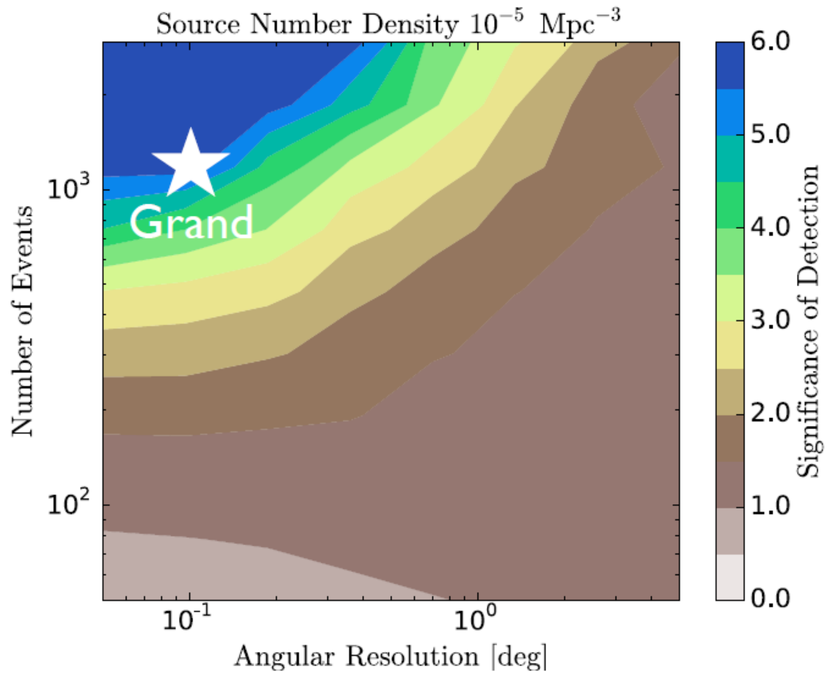
  $\sim$ 0.1 events

Multiplet analysis

- Identifying individual sources from diffuse background…
  …may be possible thanks to optimal angular resolution & large stats.



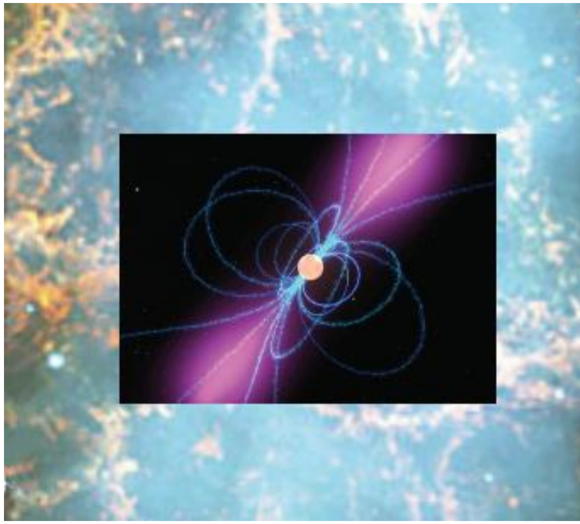
Detecting A Source On Top of the Background

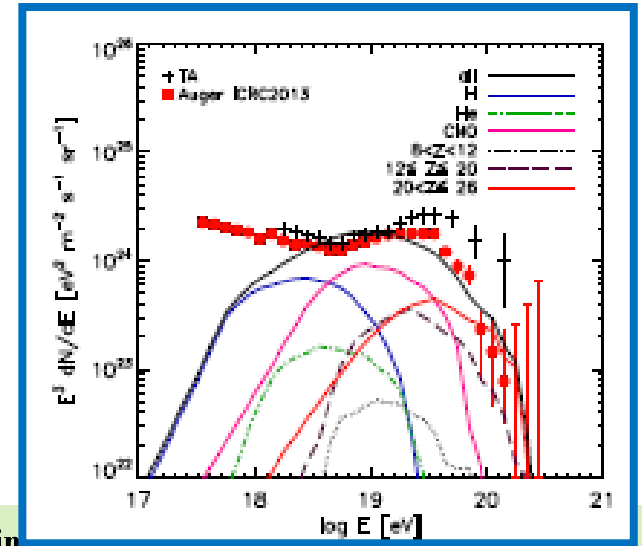


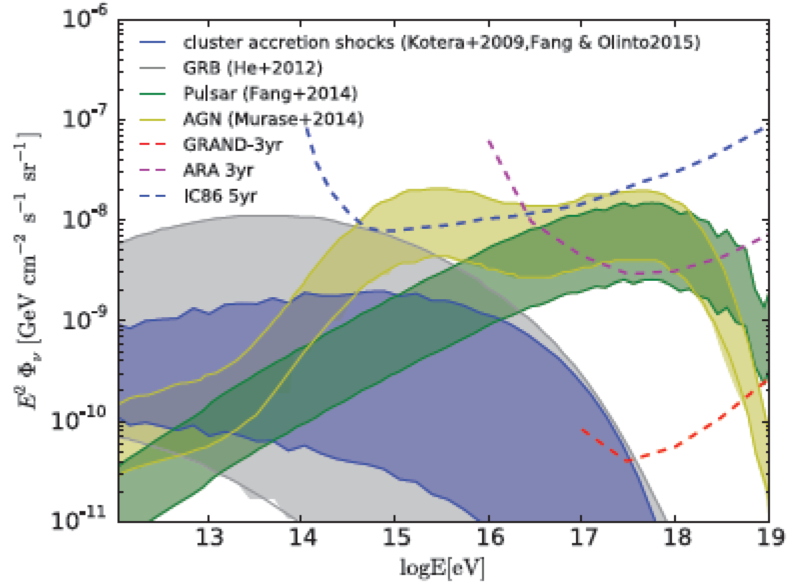
Fang, Kotera, Miller, Murase & Oikonomou, *in prep*

Young extragalctic pulsars

- Very possible source for UHECRs: [K. Fang et al., arXiv:1311.2044]
  - Matches AUGER spectrum
  - UHE heavy nuclei emmited
  - Production of neutrinos through nuclei interaction with supernova ejecta. Then $\pi^+ \longrightarrow l + \nu_l$ (= **UHE neutrinos**)





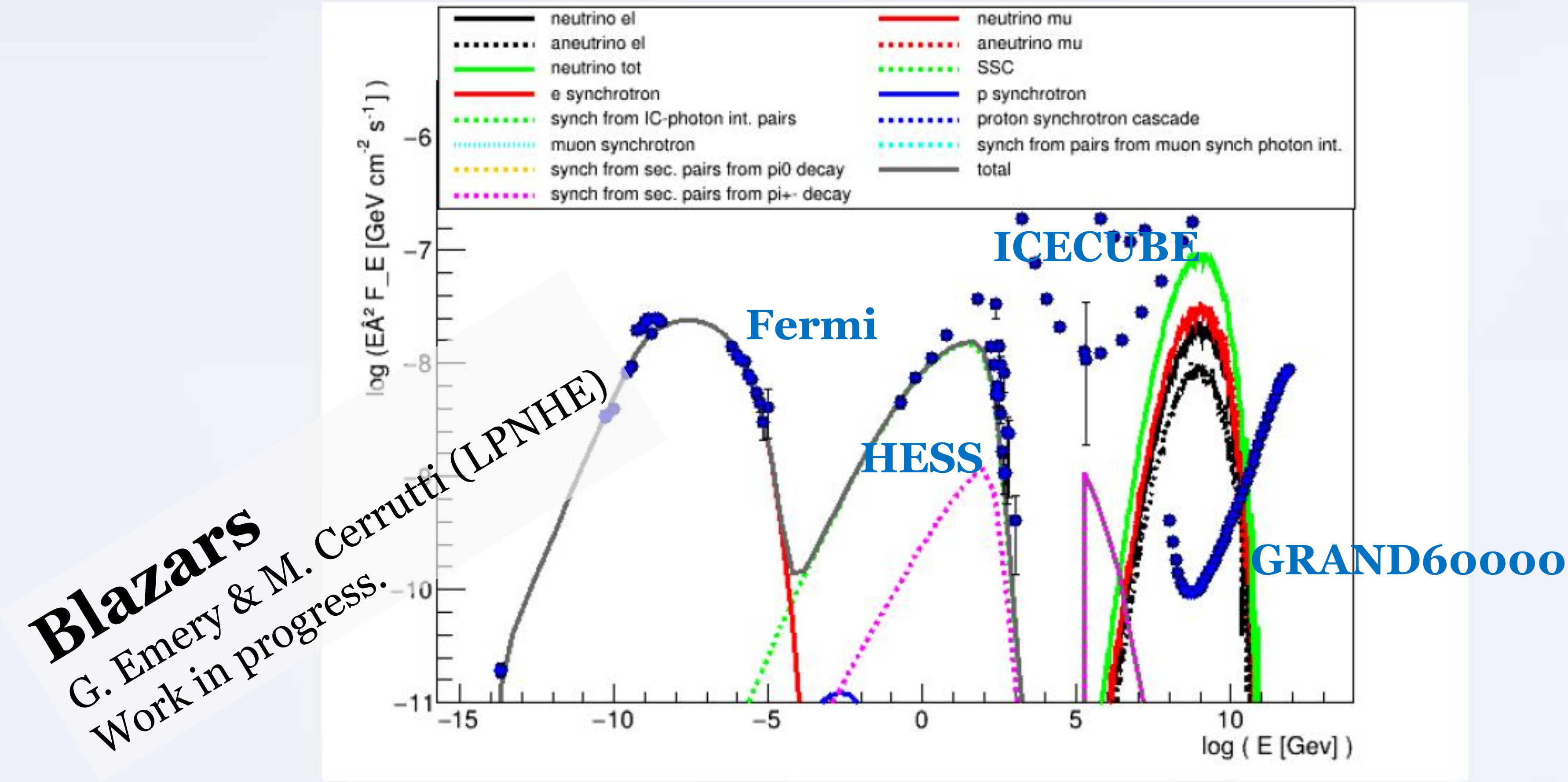


10s of events/year expected in GRAND!

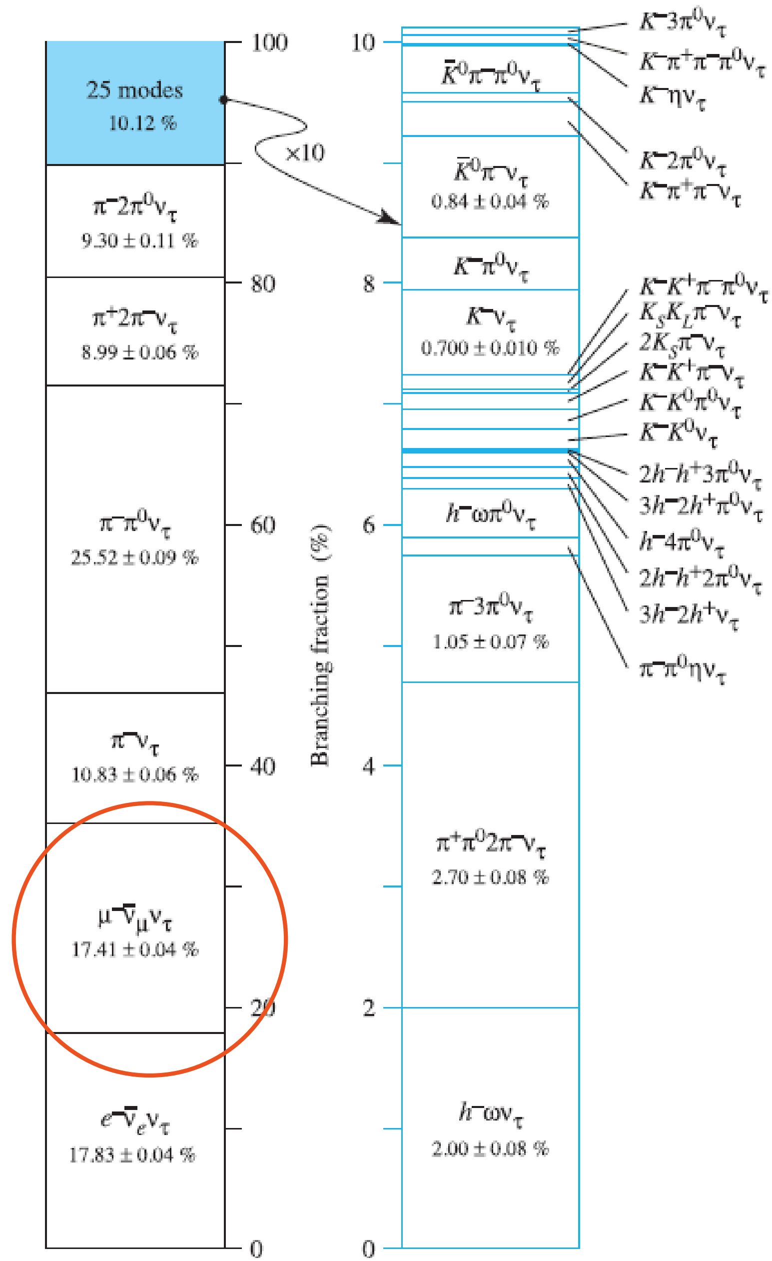
Résultats PG 1553+113

Modèle: production des photons de haute énergie par rayonnement synchrotron des protons.

Nb événements GRAND :1.8 10^{-6} s^{-1} (S_{eff} @ 89°)
➔ 5.6 evts/an attendus (ouverture angulaire de 4°)

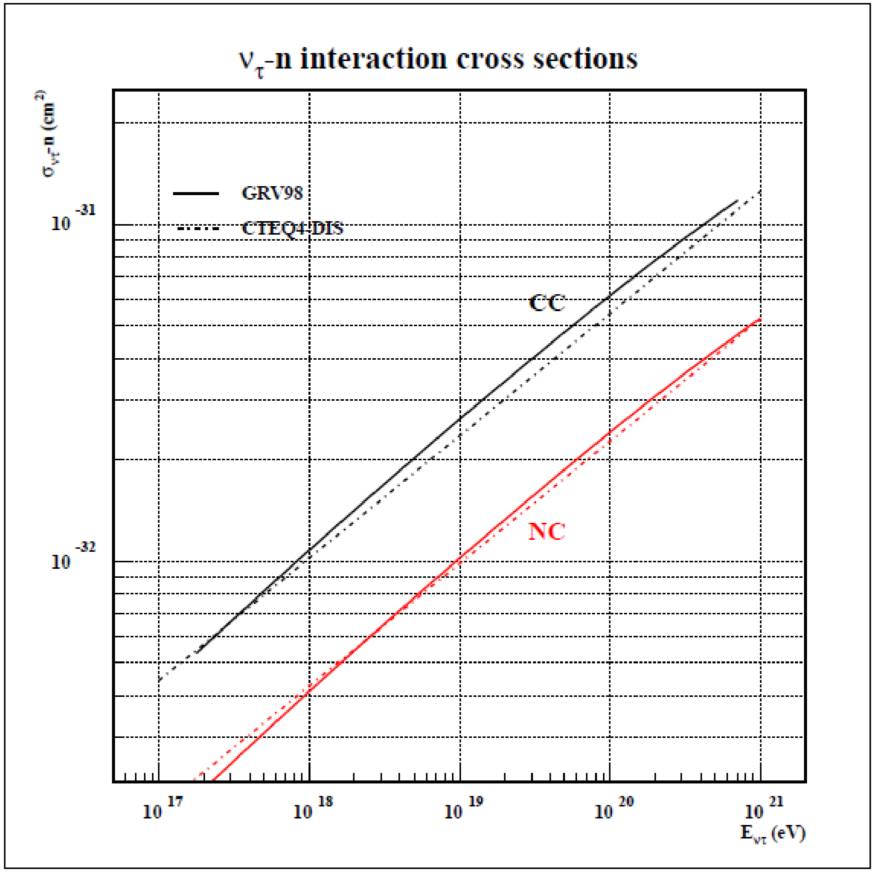


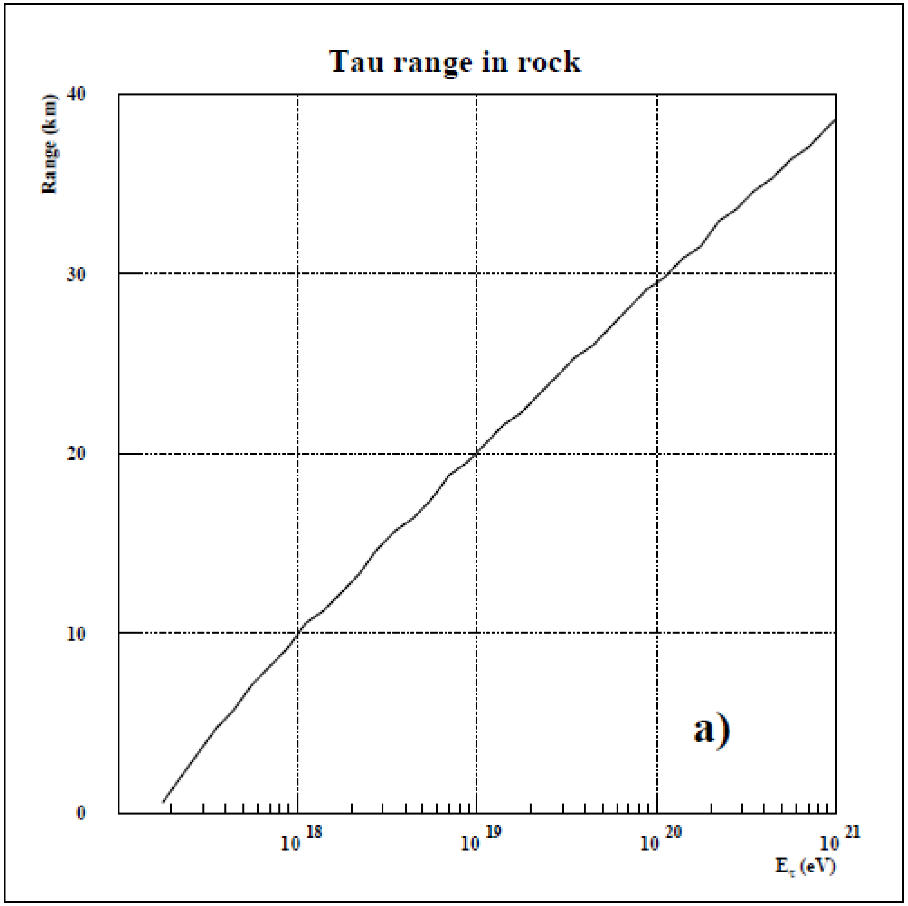
τ decay branching ratio



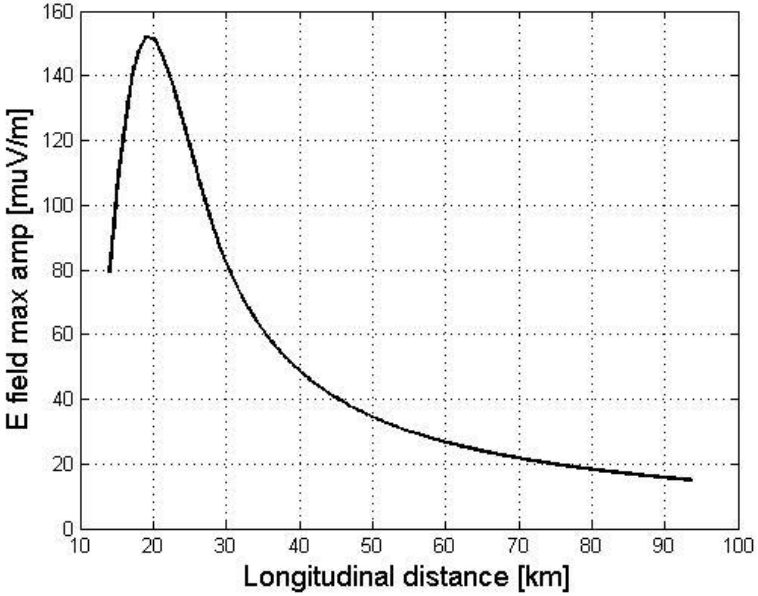
The neutrino simulation ingredients

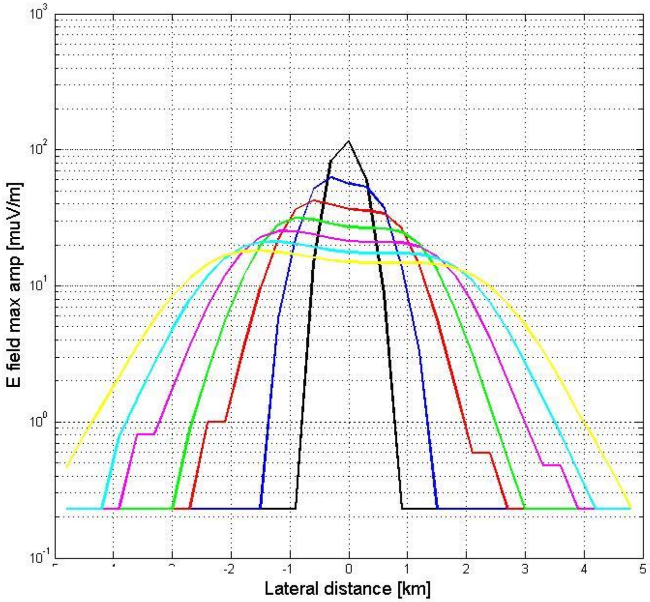
- **ν Deep Inelastic Scattering (DIS)** in the rocks:
  - Integrated cross sections from Gandhi et al. (CTEQ4-DIS), but inelasticity randomised with Pythia CTEQ5d pdf.
  - The neutrino is tracked until a CC interaction occurs, its energy falls below a threshold (1 PeV typically) or it escapes the simulation 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.

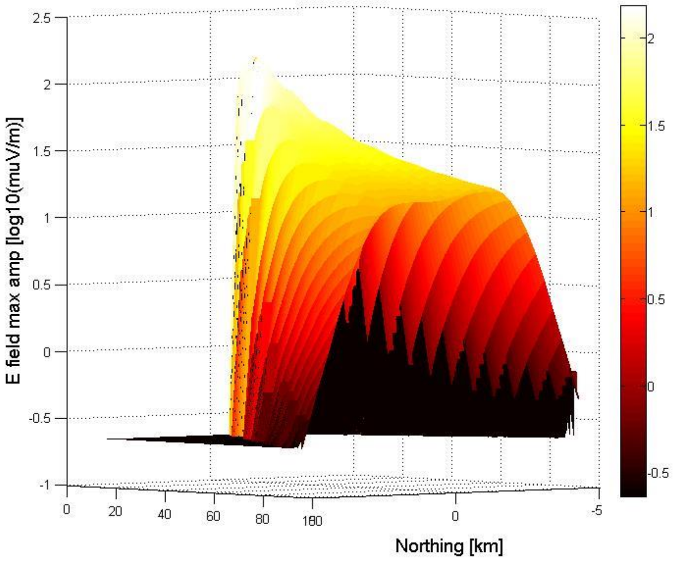

ν_τ-n interaction cross sections
$\sigma_{\nu\tau}$-n (cm^2)
GRV98
CTEQ4-DIS
CC
NC
10^{-31}
10^{-32}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
$E_{\nu\tau}$ (eV)


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

ZHAireS shower profile



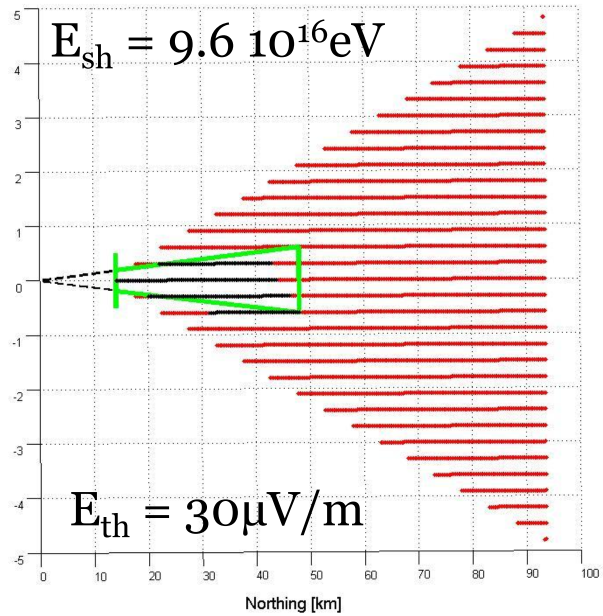


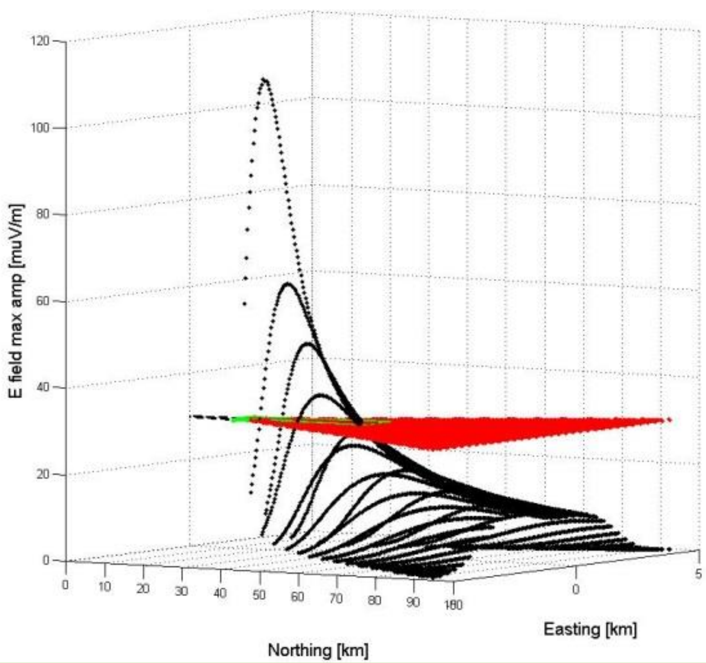


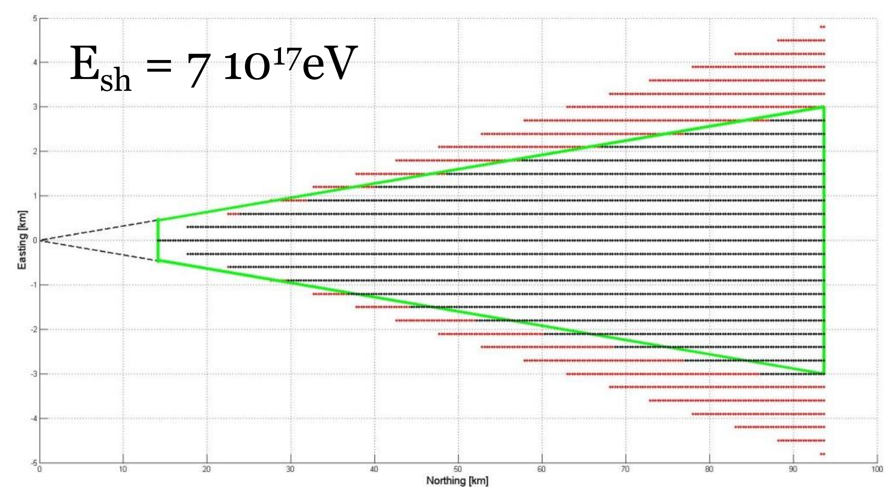
GRAND shower parametrization

- Determine volume with $\mathcal{E} > \mathcal{E}_{th}$ ($\mathcal{E}_{th}$ = 30 or 100μV/m)
- **Conical parametrization** of this «trigger volume»

	Agressive: $\mathcal{E}_{th}$ = 30 μV/m		Conservative: $\mathcal{E}_{th}$ = 100 μV/m	
	Ω (deg)	Range (km)	Ω(deg)	Range (km)
10^{17} eV	0.9	[14,55]	0.45	[14,22]
10^{20} eV	3	[14,234]	2.3	[14,146]

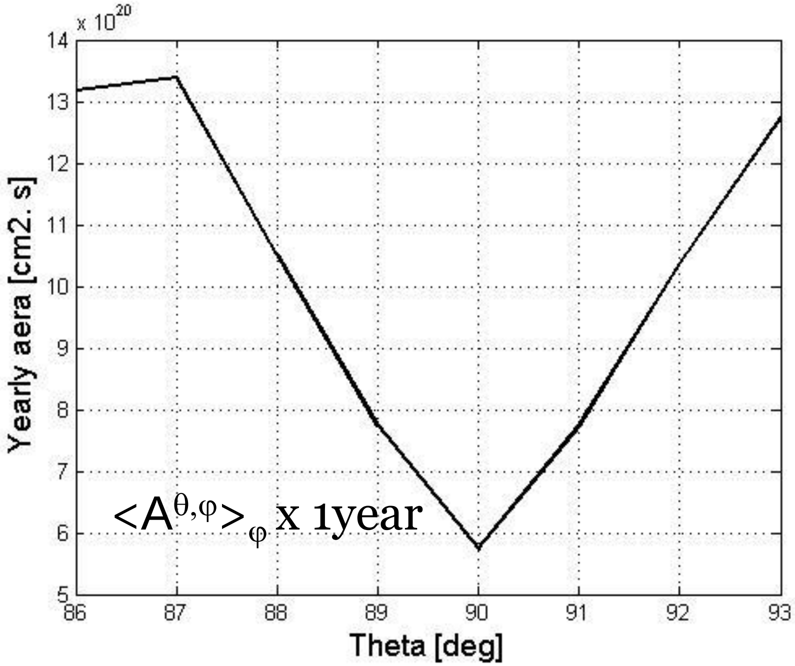






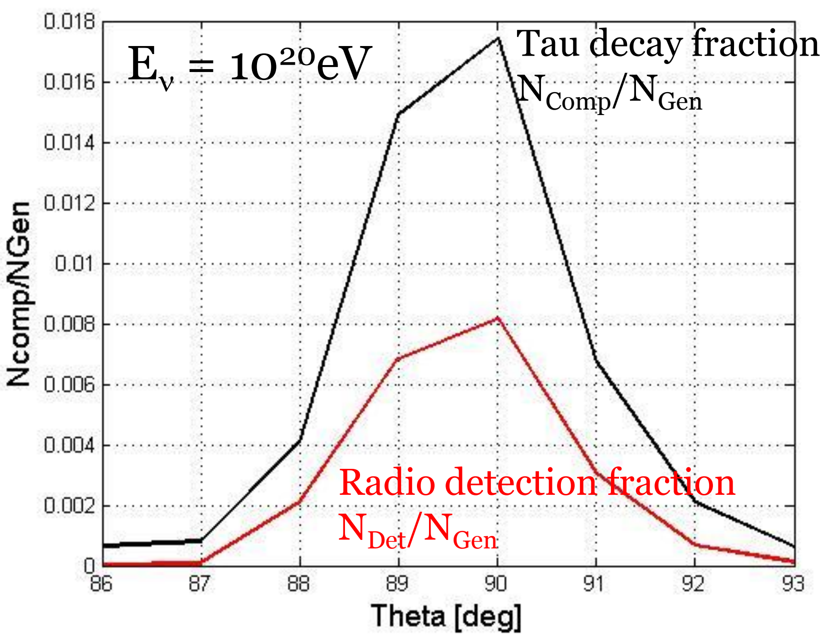
he G

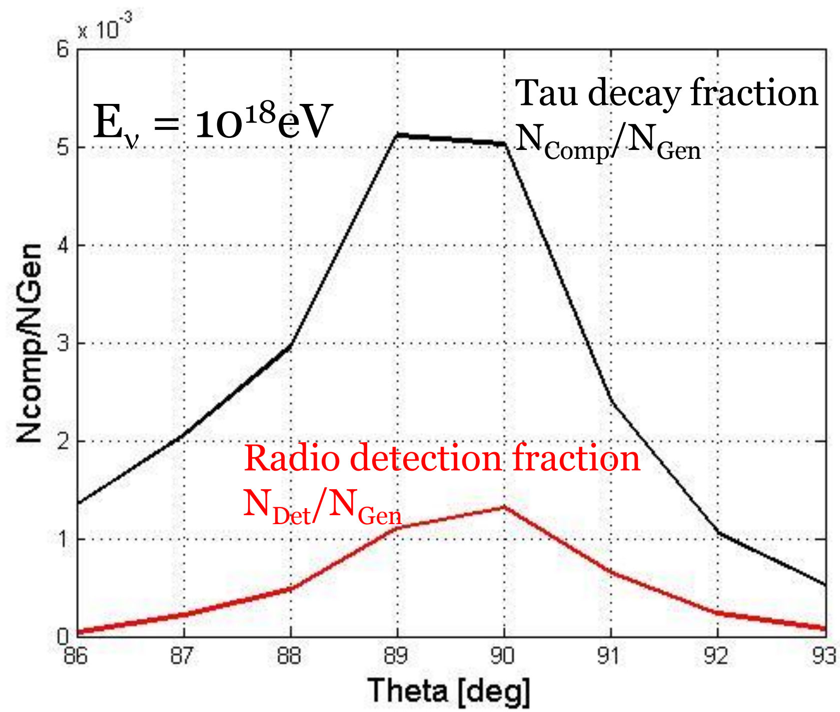
GRAND preliminary
ν sensitivity study



$$2\pi \int < A^{\theta,\varphi} > \frac{N_{Det}}{N_{Gen}} \sin\theta d\theta \times 1year \ = 1.7\ 10^{18}\ cm^2.sr.s\ @10^{20}eV$$

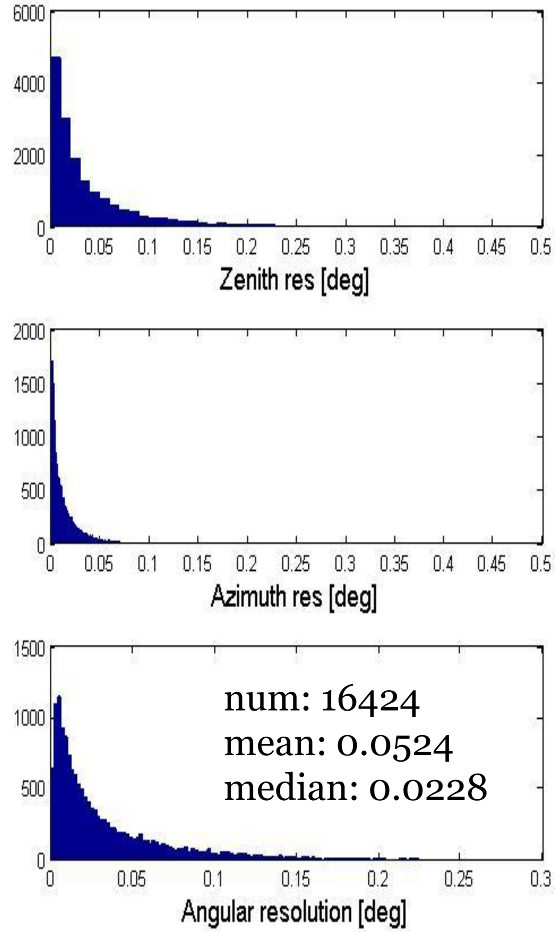
$$2\pi \int < A^{\theta,\varphi} > \frac{N_{Det}}{N_{Gen}} \sin\theta d\theta \times 1year \ = 3.4\ 10^{17}\ cm^2.sr.s\ @10^{18}eV$$

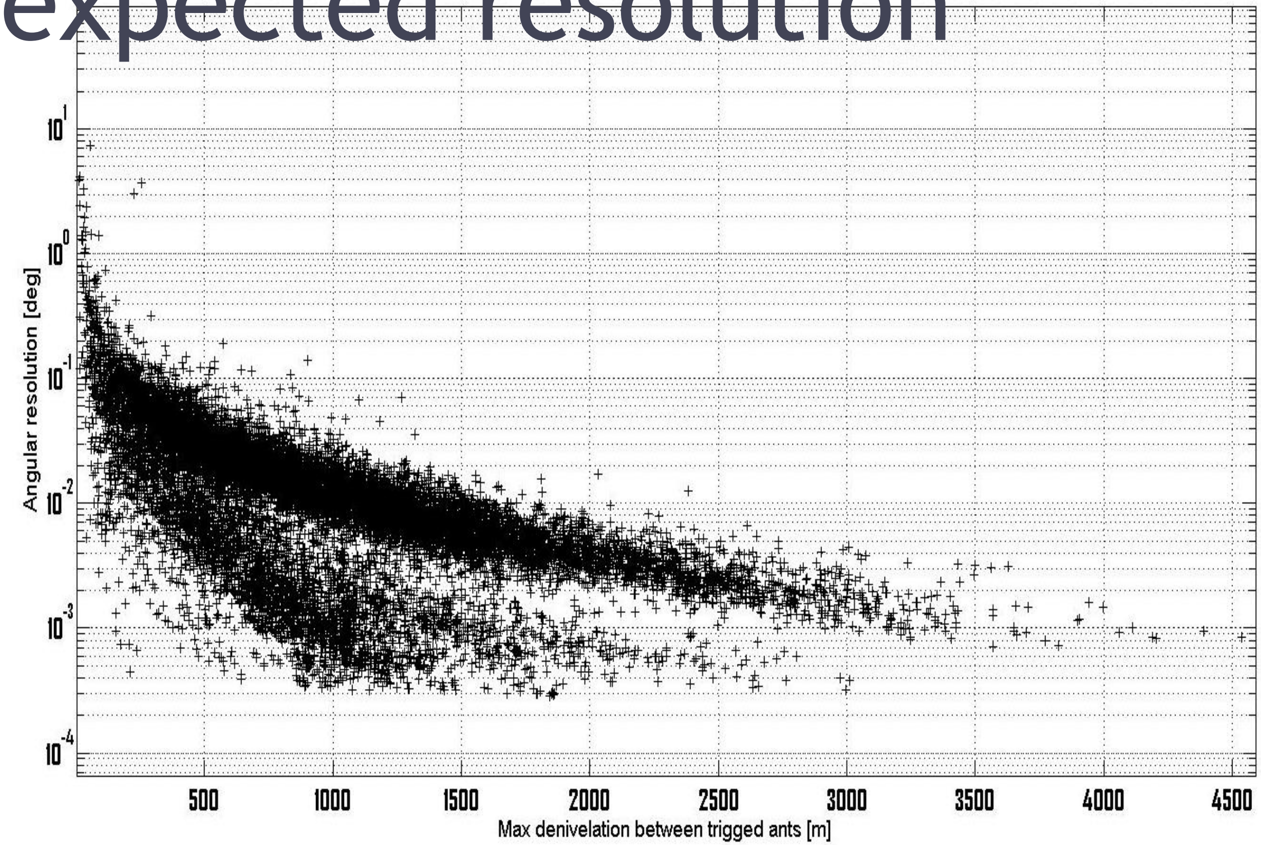


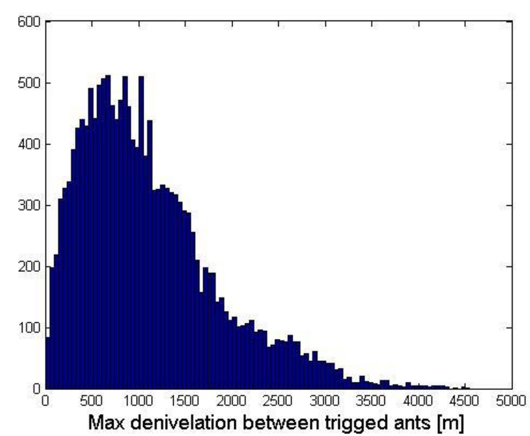


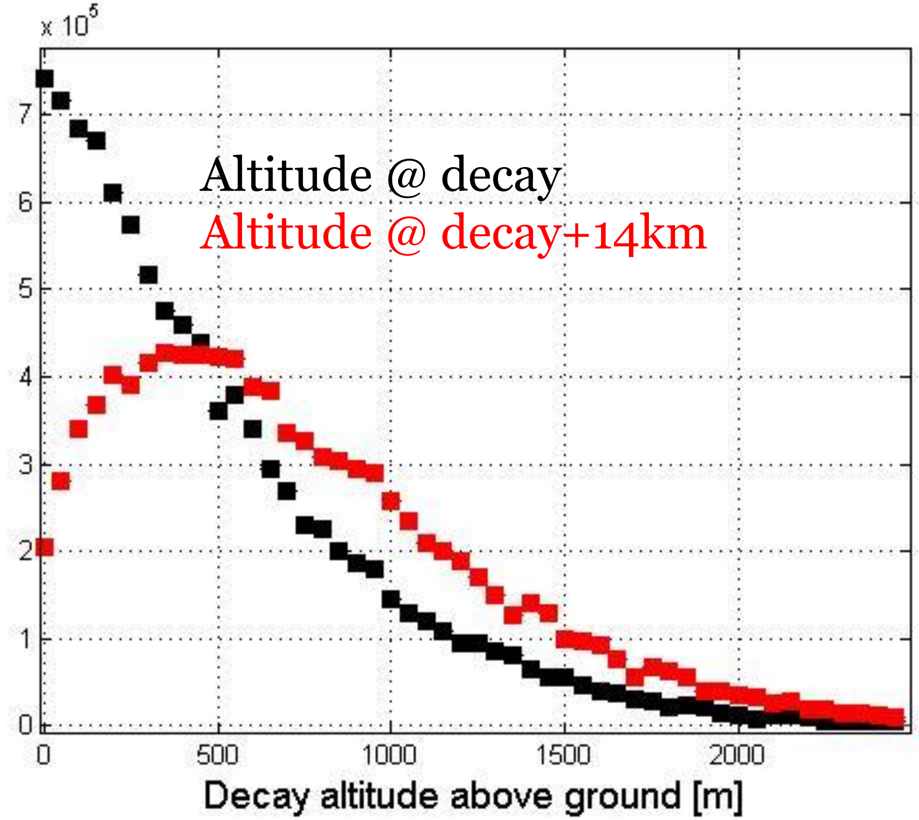
GRAND expected resolution

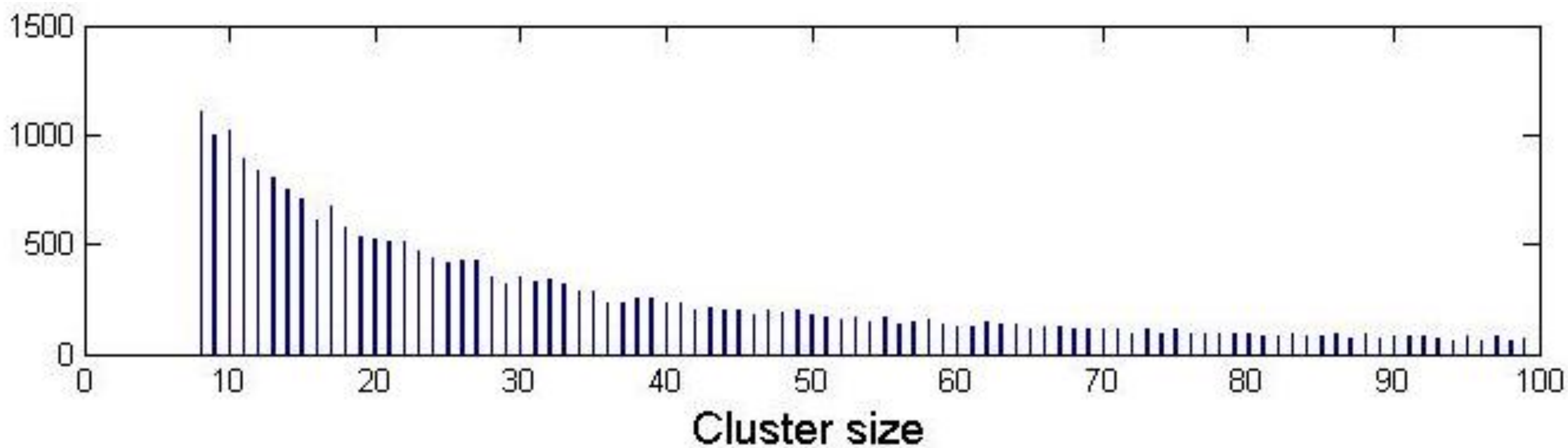
Cut out events with max deniv<100m (2% of events)





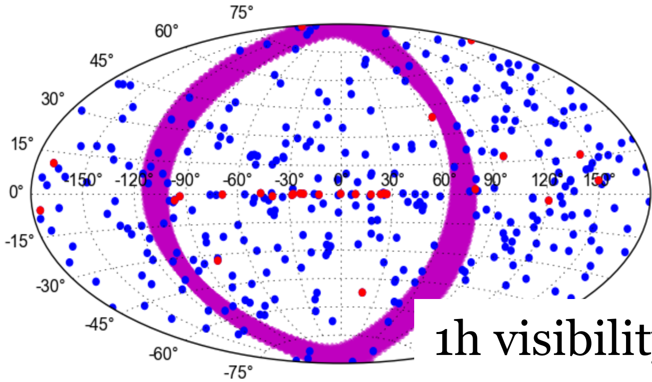



x 10^5
Altitude @ decay
Altitude @ decay+14km
0
1
2
3
4
5
6
7
0
500
1000
1500
2000
Decay altitude above ground [m]

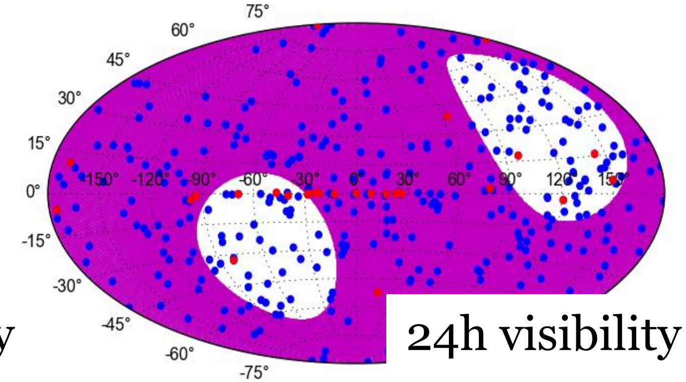

1500
1000
500
0
0
10
20
30
40
50
60
70
80
90
100
Cluster size

GRAND ν sensitivity study - Results

- Field of view
  (JP Lenain)

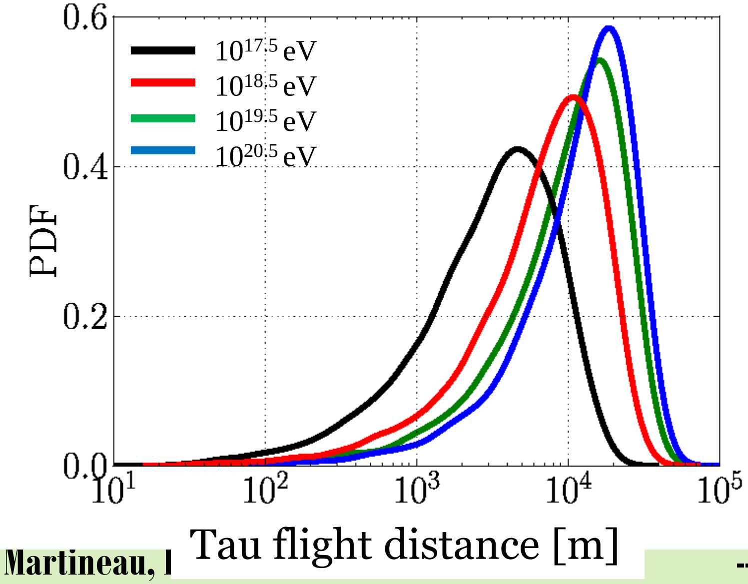


1h visibility

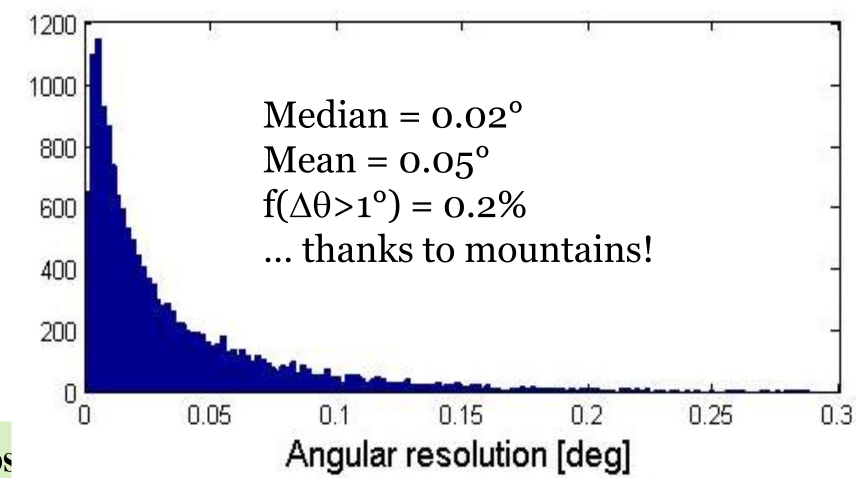


24h visibility

- 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 (?)



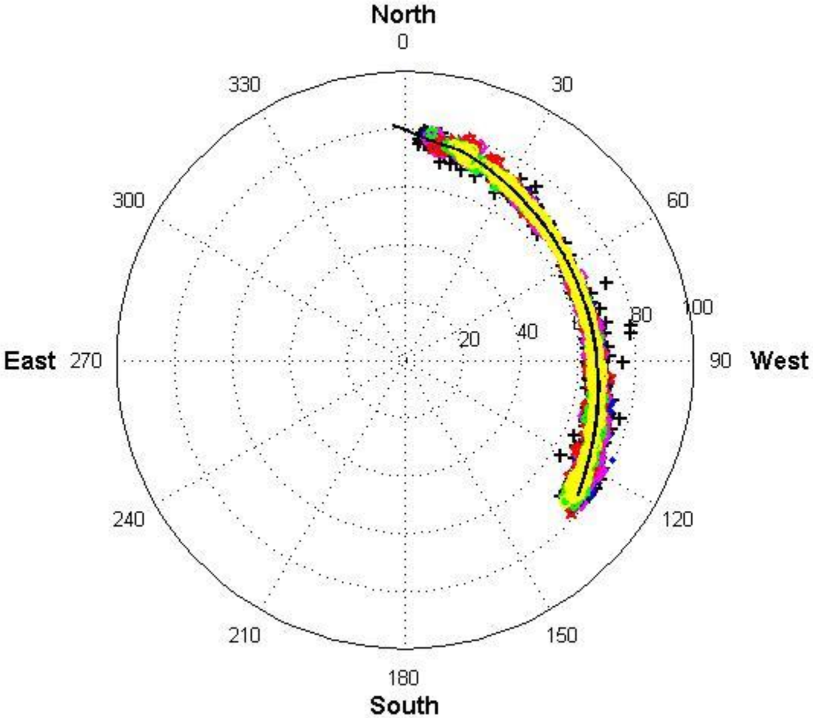
- Angular resolution
  - Analytical computation assuming 3ns trigger timing precision (no noise).
  - Mean = 0.05°: full benefit of extended trigger zone & denivelation.

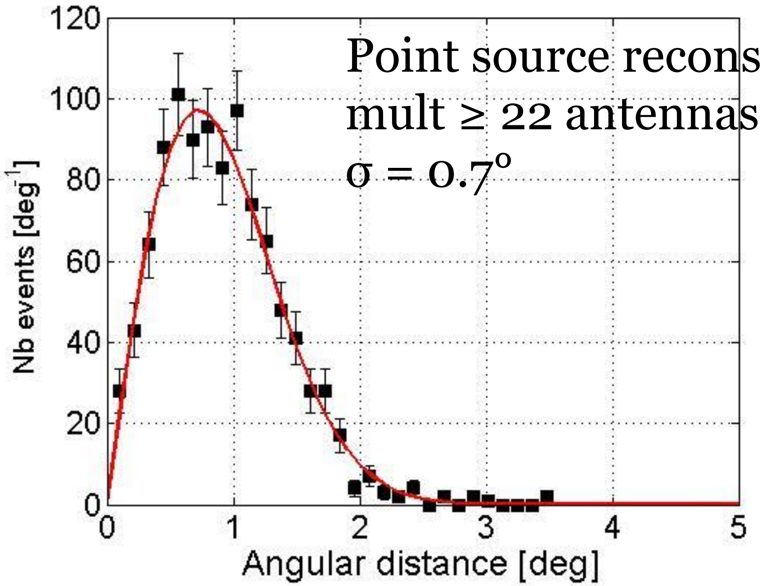


RADIO PERFORMANCES: DIRECTION RECONSTRUCTION

- **Plane track**

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

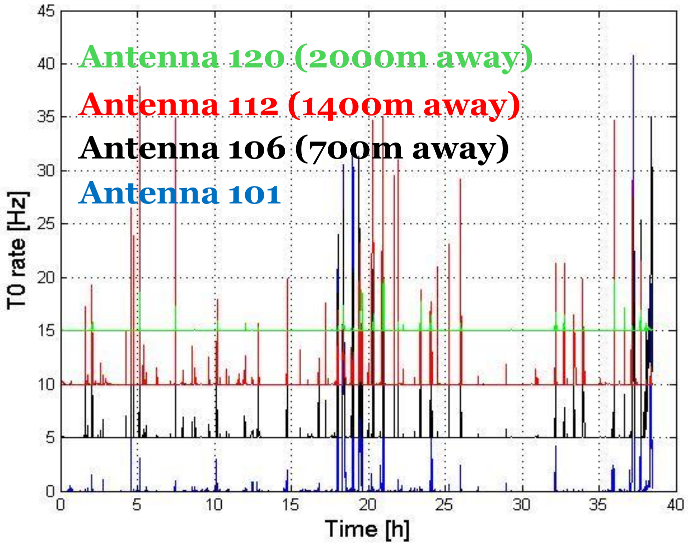




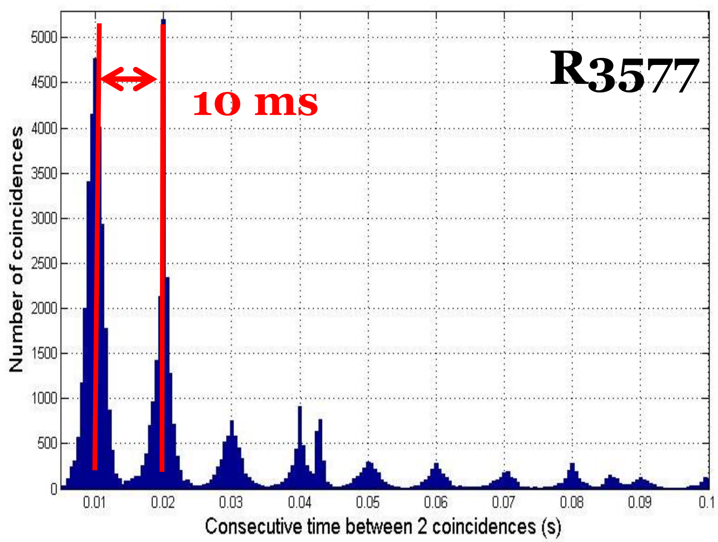
Total angular resolution <1.5° on the track
(and improves with smaller zenithal angle)

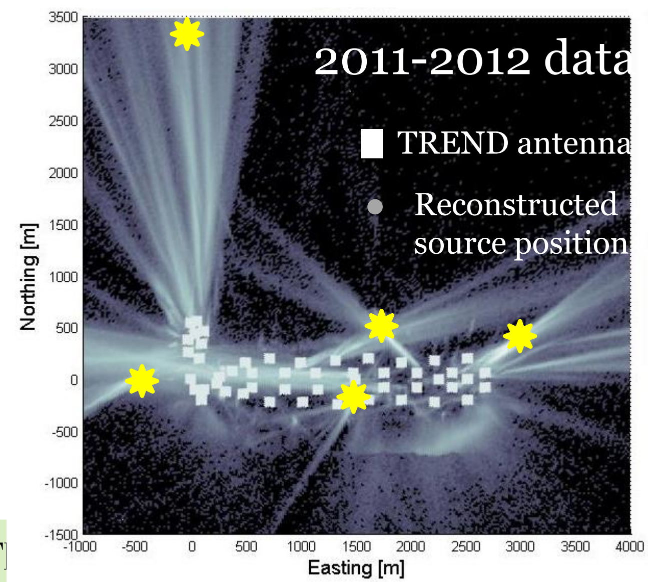
Estimated antenna trigger timing error: ±10ns

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.**





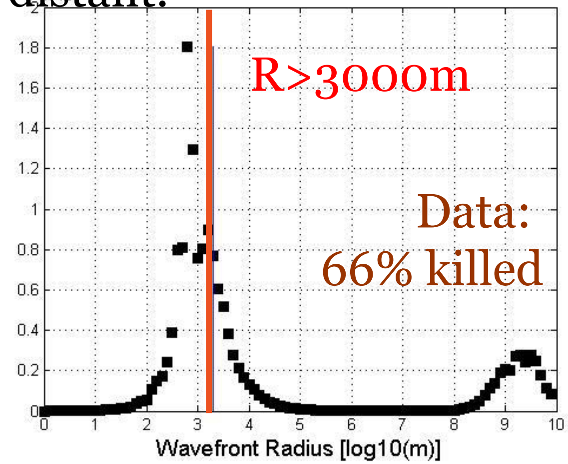
<u>2011-2012 data:</u>
317 DAQ days analyzed

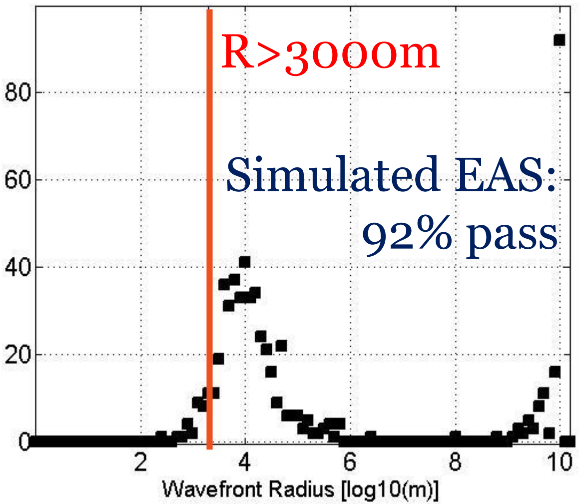
3.7 10^9 triggers recorded
2.4 10^8 coincidences
<u>~10Hz</u> average coinc rate over whole array

(~20 EAS/day expected)

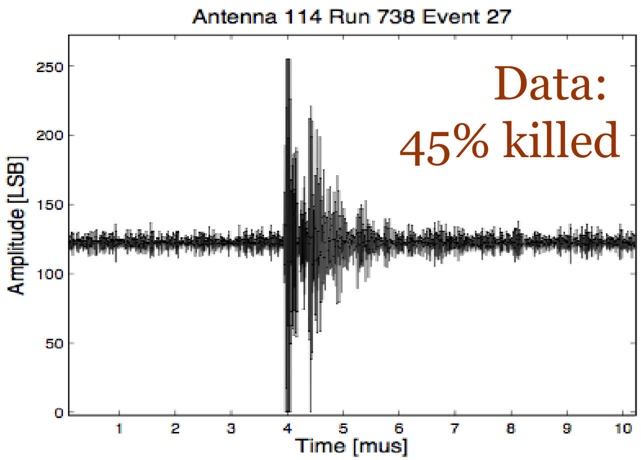
Discriminating parameters

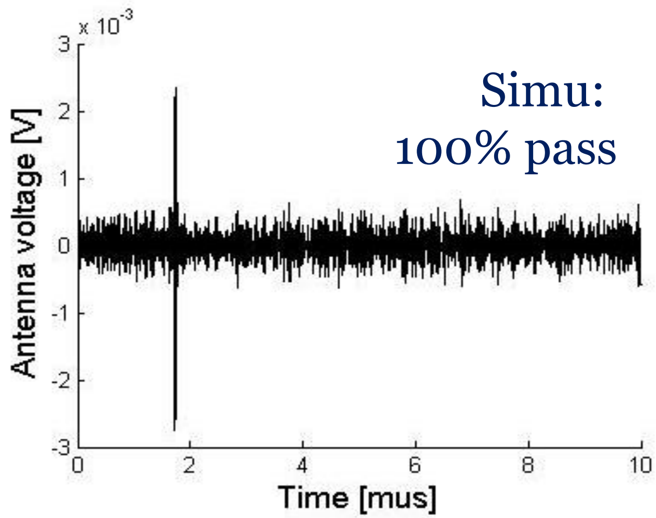
- Spherical wave recons: point source reconstruction of backgrd sources close to array, EAS more distant.





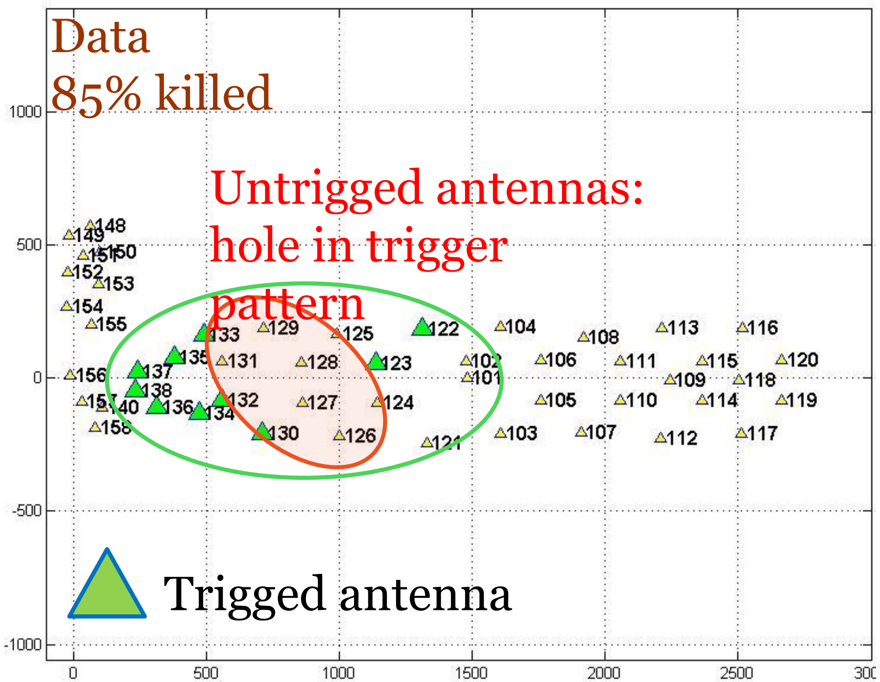
- Signal shape: prompt signal for EAS

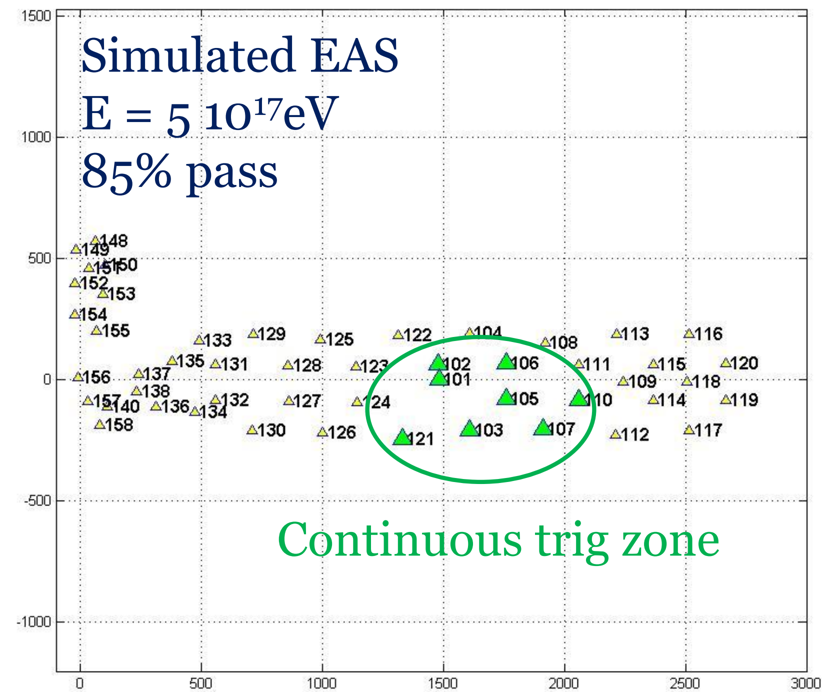




Discriminating parameters

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

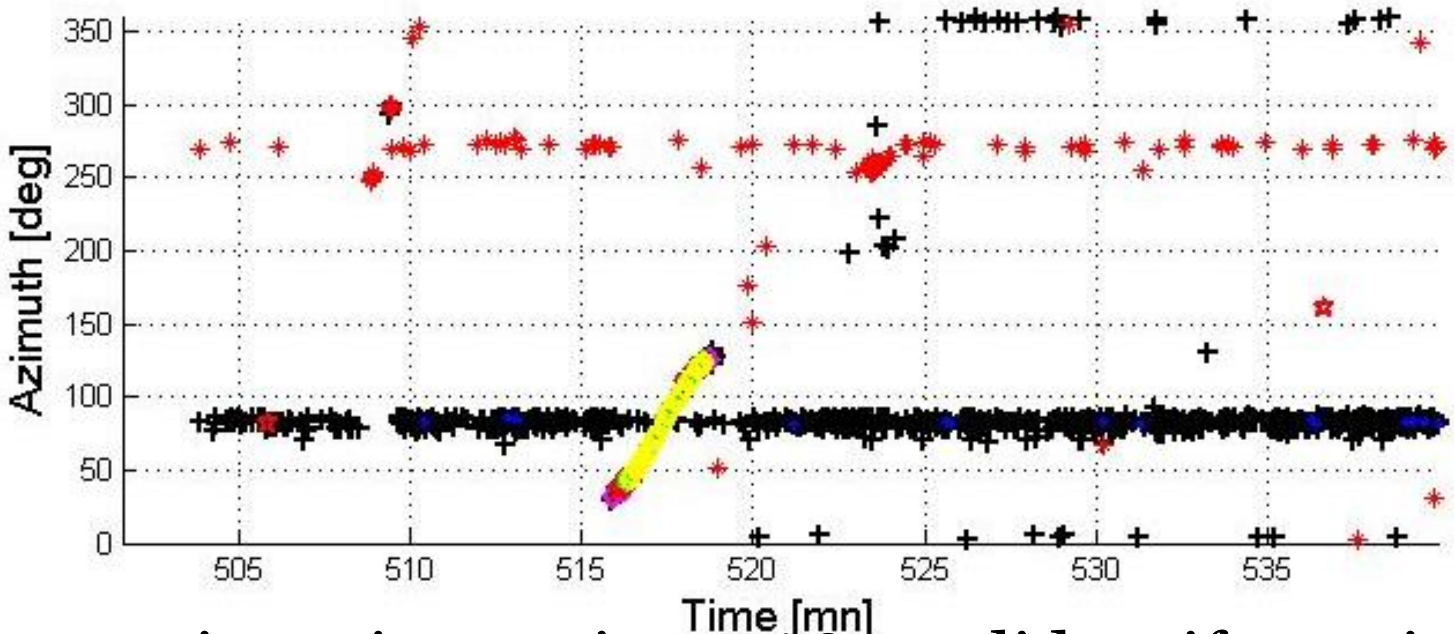




Limited array size + monopolar antennas (+ system unreliability) reduce cut efficiency.

Environment cuts

- Bckgd events strongly correlated in time & space



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

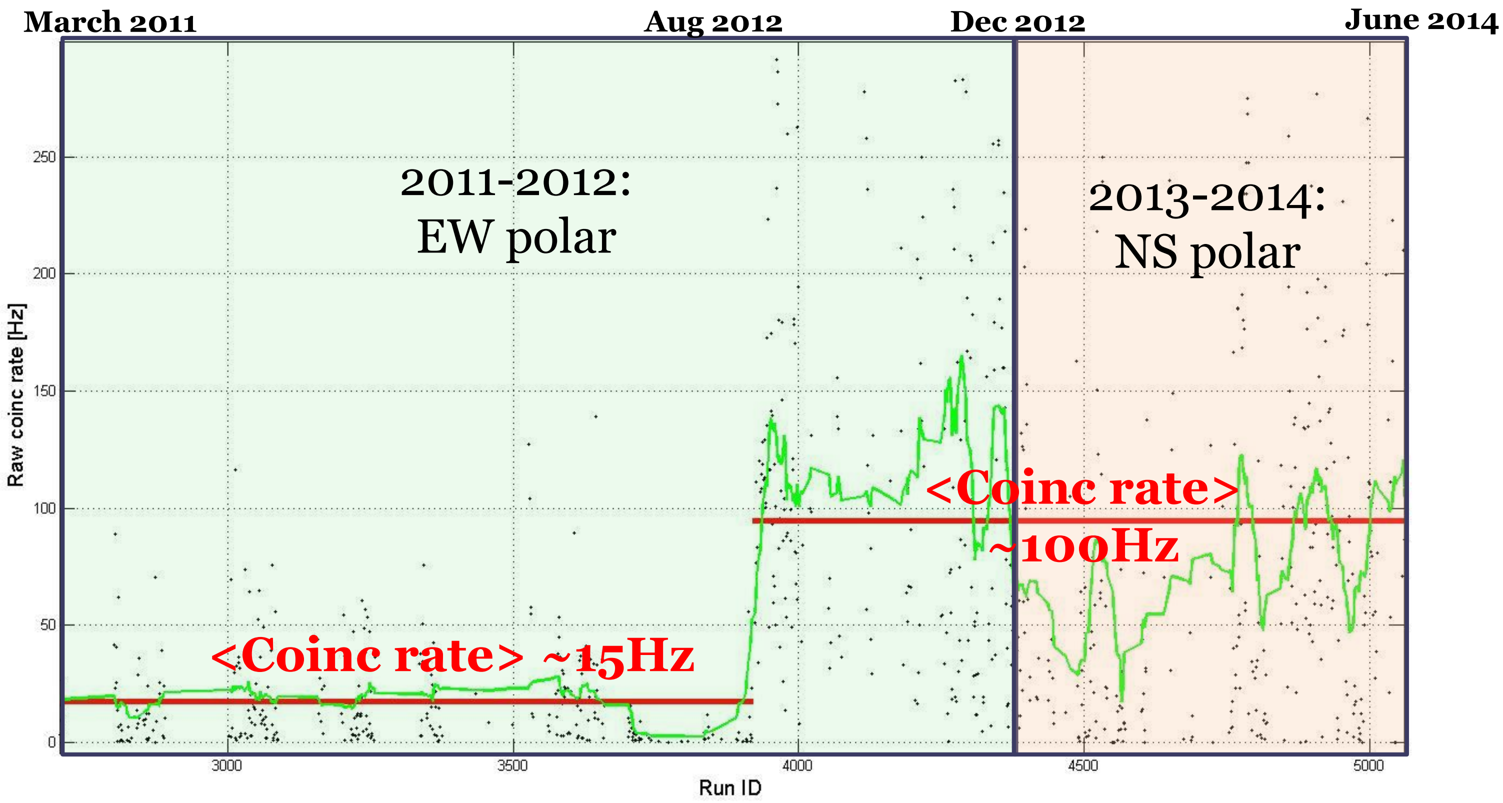
Cut efficiency:
from 2.4 10^8 to 465 events

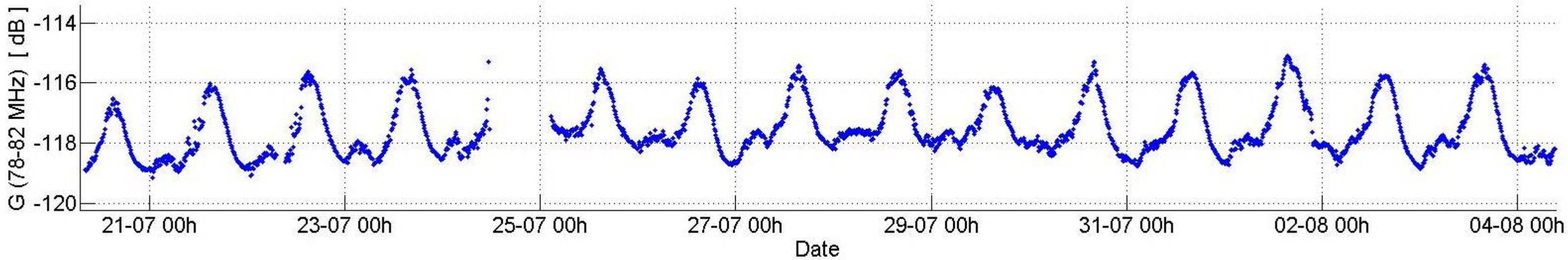
Cut	% survival	N_{coincs} final	Simu % survival
« 50Hz » cut	24%	5.9 10^7	To be determined
Pulse duration	56%	3.3 10^7	100%
Multiplicity > 4	57%	1.9 10^7	-
Valid direction reconstruction	79%	1.5 10^7	100%
Radius > 3000m	33%	5 10^6	92%
$\Theta < 80°$	14%	7 10^5	/
Trigger pattern/ Extension	15%	10^5	85%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

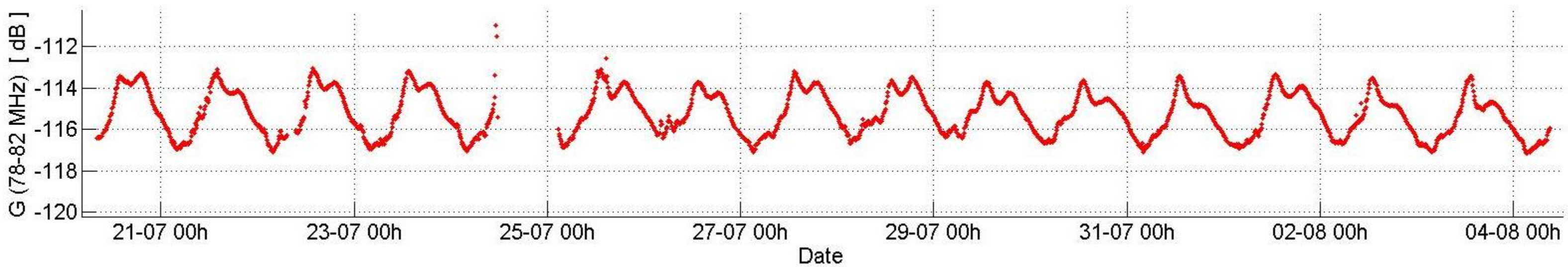
No cut is related to wave (absolute) arrival direction.

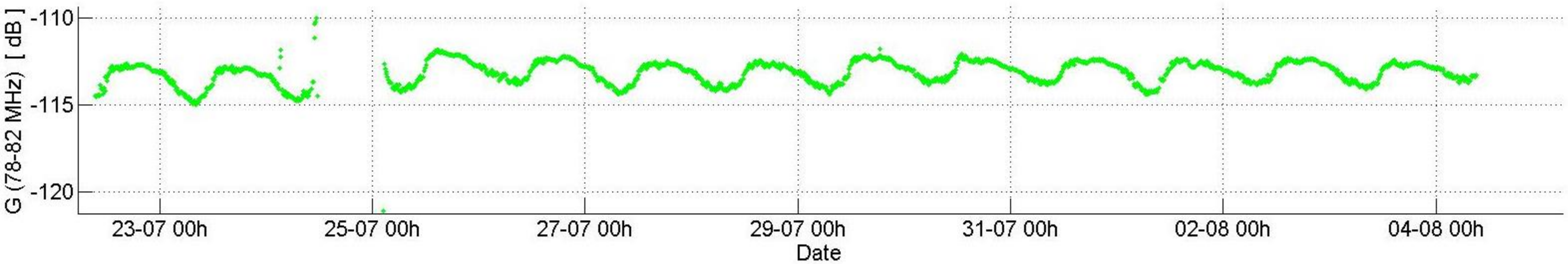
TREND-50 2013-2014

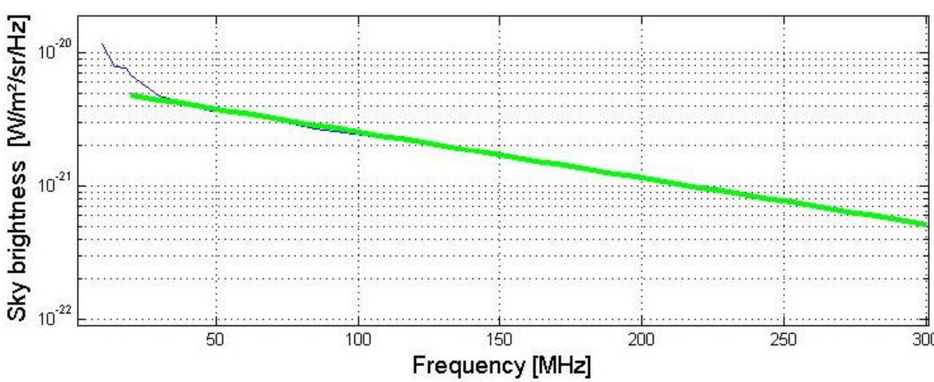
- Possible causes for much fewer candidates:
  - Array maintenance degraded (>30% antennas off)
  - Bckgd noise significantly higher, affects DAQ duty cycle & acceptance (environment cuts)

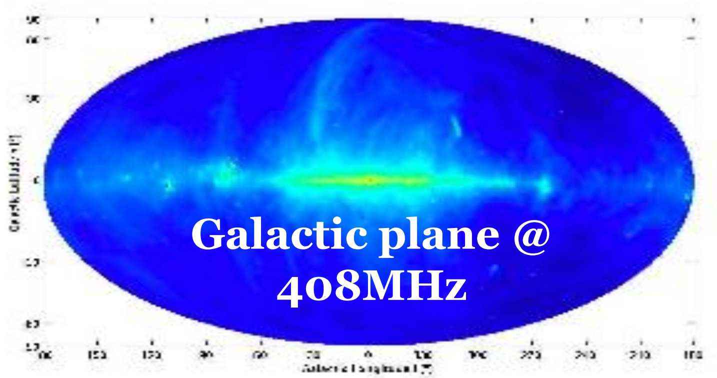



G (78-82 MHz) [dB]
-114
-116
-118
-120
21-07 00h
23-07 00h
25-07 00h
27-07 00h
29-07 00h
31-07 00h
02-08 00h
04-08 00h
Date


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

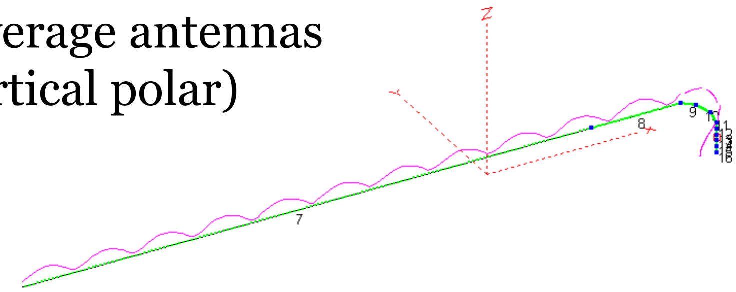

Sky brightness [W/m²/sr/Hz]
10^{-20}
10^{-21}
10^{-22}
50
100
150
200
250
300
Frequency [MHz]

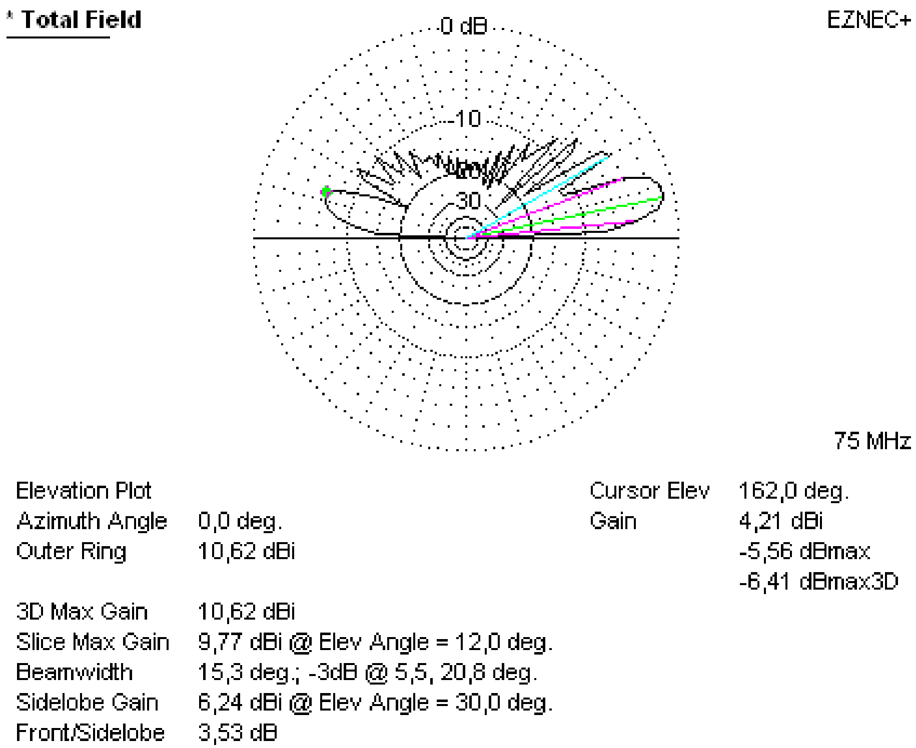

Galactic plane @ 408MHz

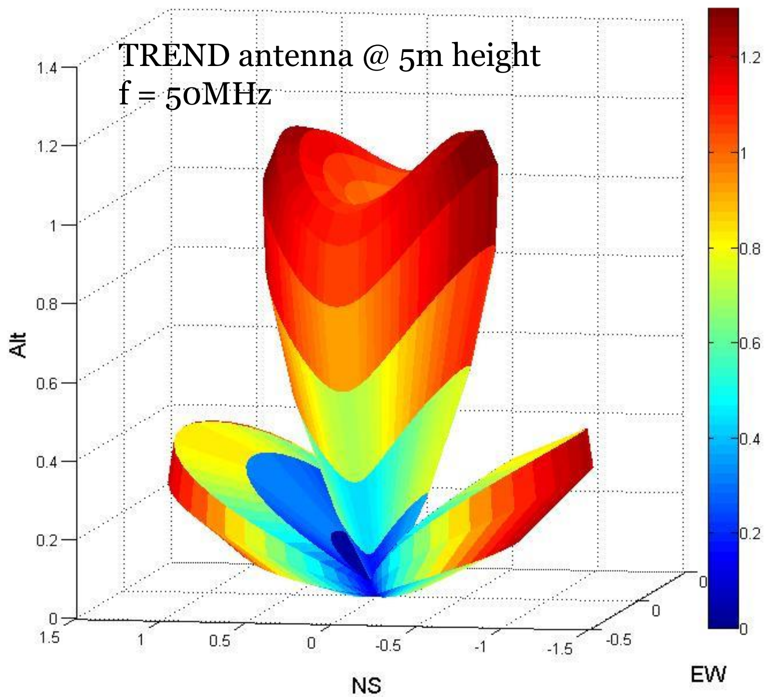
GRAND antennas

- Define optimal GRAND antenna design:
  - **Good sensitivity at large zenith angle.**
  - Azimuthal directivity?
  - (No) sensitivity towards zenith (⇔ background noise level)?
  - Frequency range?
  - Robustness & simplicity (200000 units)
  - **... Requires serious R&D by experienced specialist.**

Beverage antennas (vertical polar)

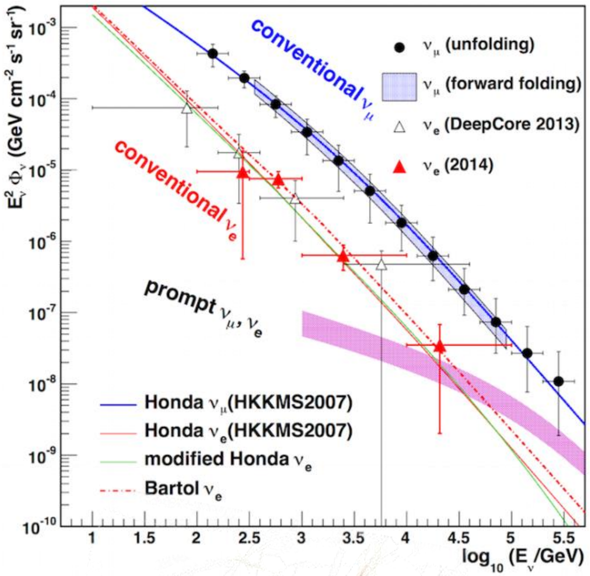






Neutrino cosmic background

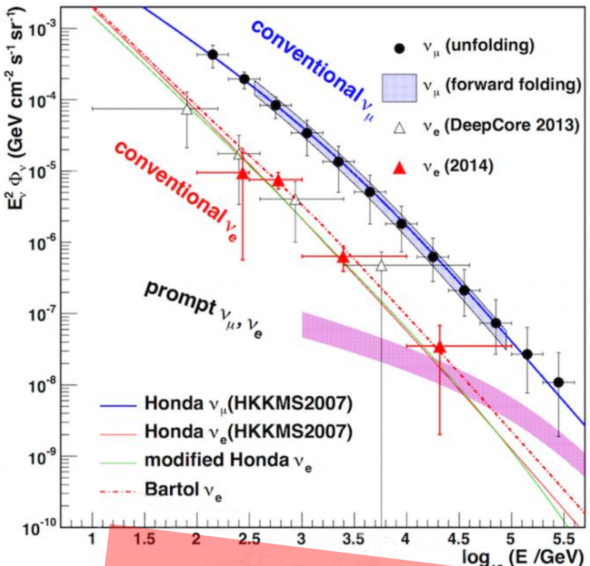
Sensitivity limit for 0 candidates within 3 years…
=> Background rejection is a major challenge.



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

Neutrino cosmic background

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



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      ⇨ larger X_{max}
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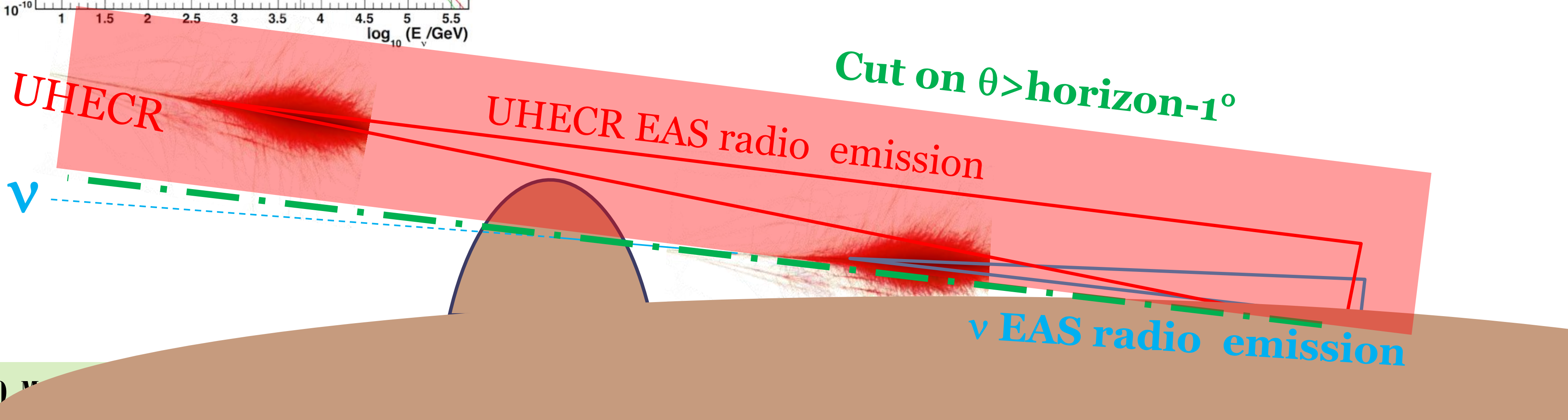
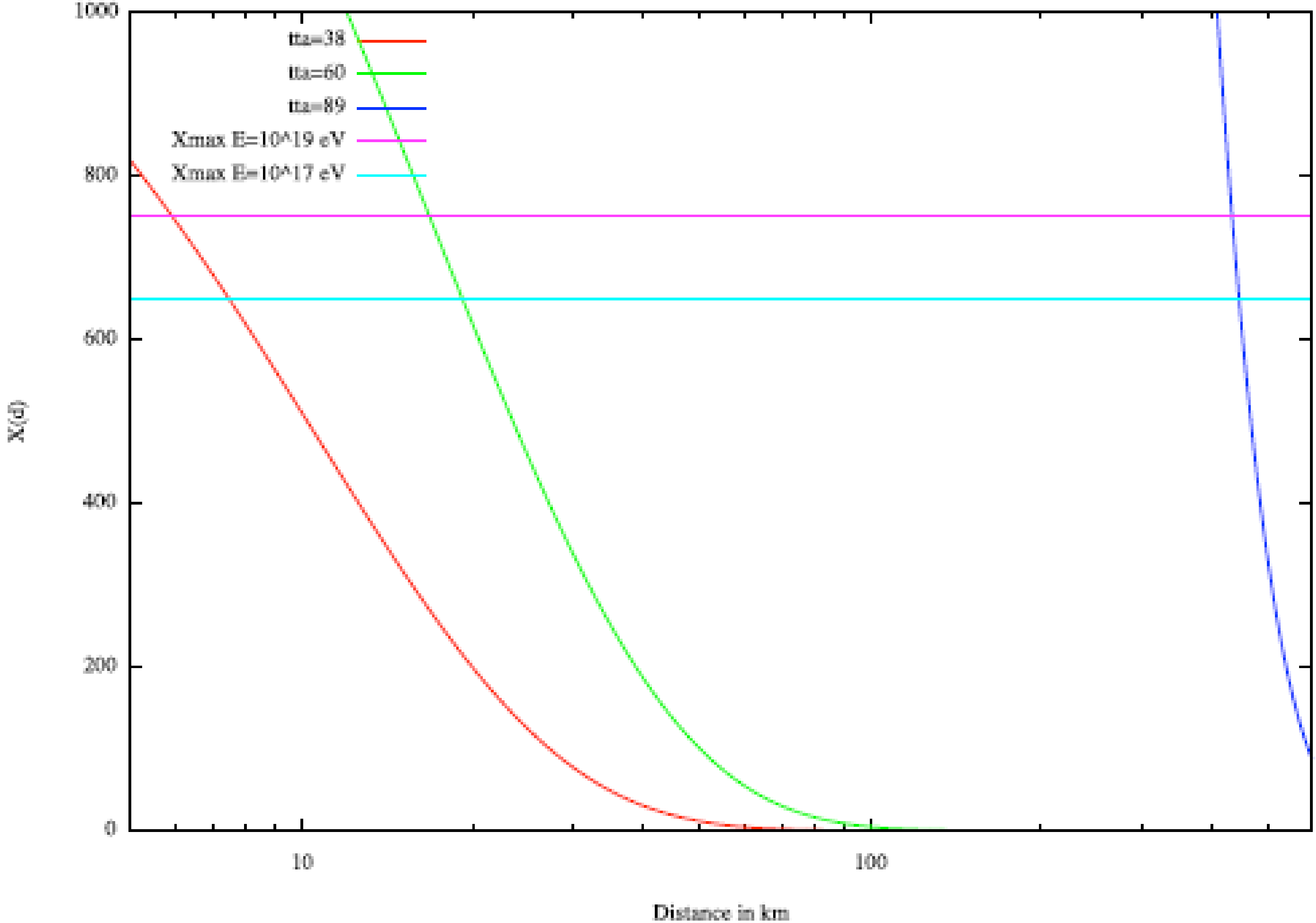
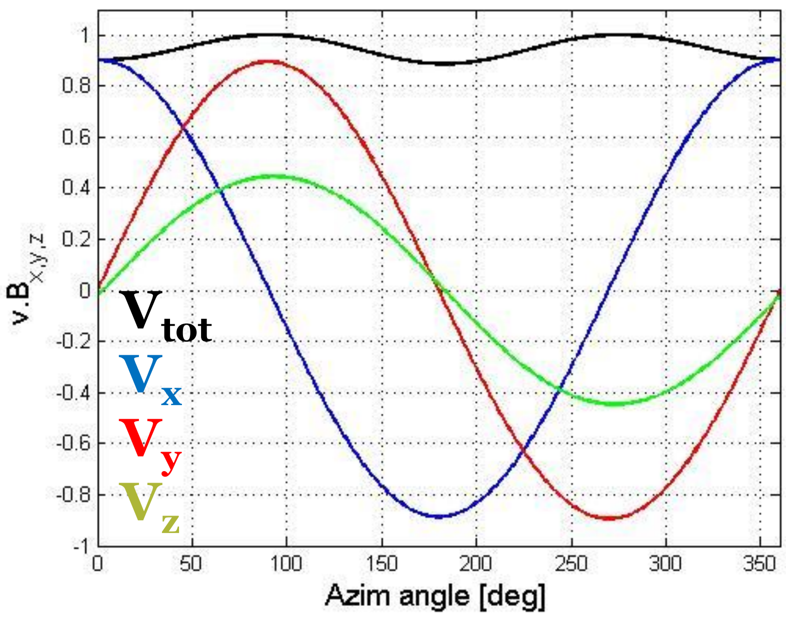
    - Cut on reconstructed zenith angle θ> horizon - 1° kills large fraction of background thanks to angular resolution.



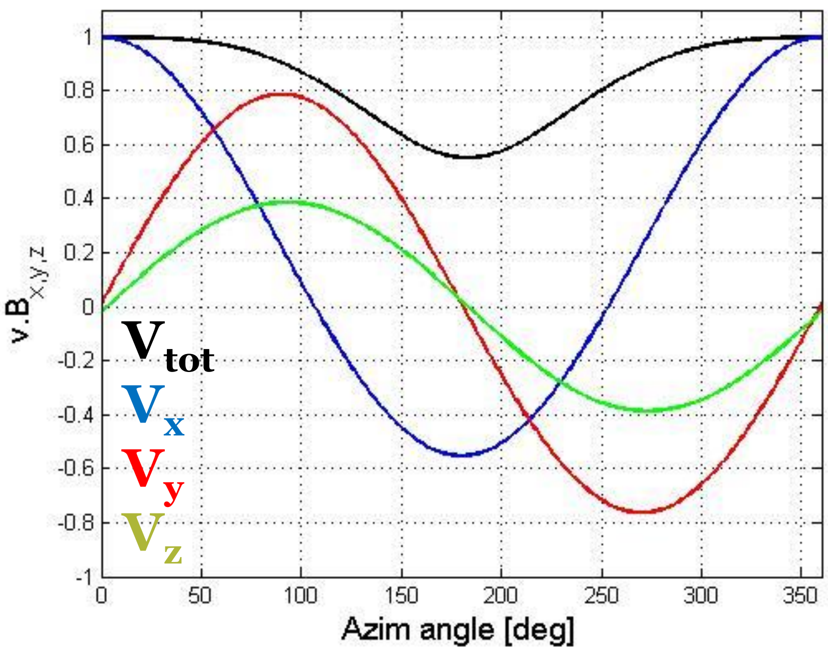

tta=38
tta=60
tta=89
Xmax E=10^19 eV
Xmax E=10^17 eV
1000
800
600
400
200
0
X(d)
10
100
Distance in km

θ = 89°



1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
50
100
150
200
250
300
350
Azim angle [deg]
v.B x,y,z
V tot
V x
V y
V z

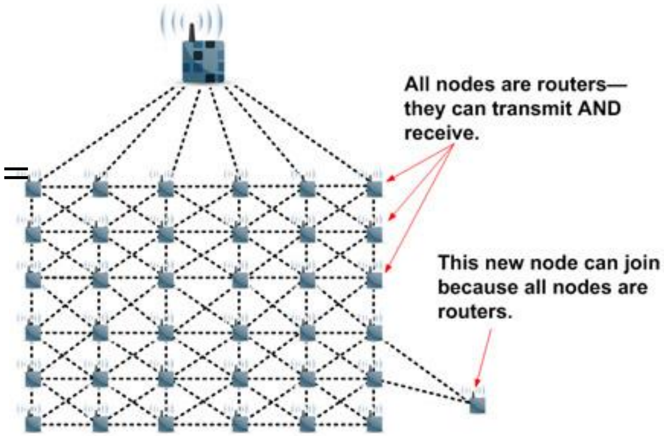
θ = 60°

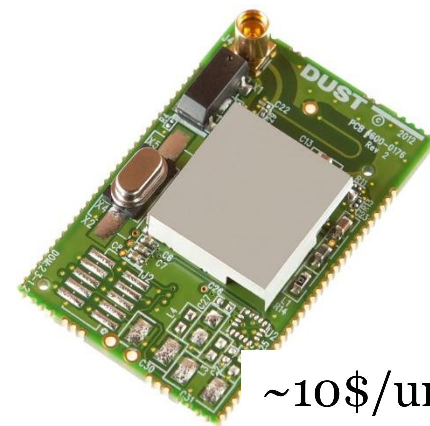


1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
50
100
150
200
250
300
350
Azim angle [deg]
v.B x,y,z
V tot
V x
V y
V z

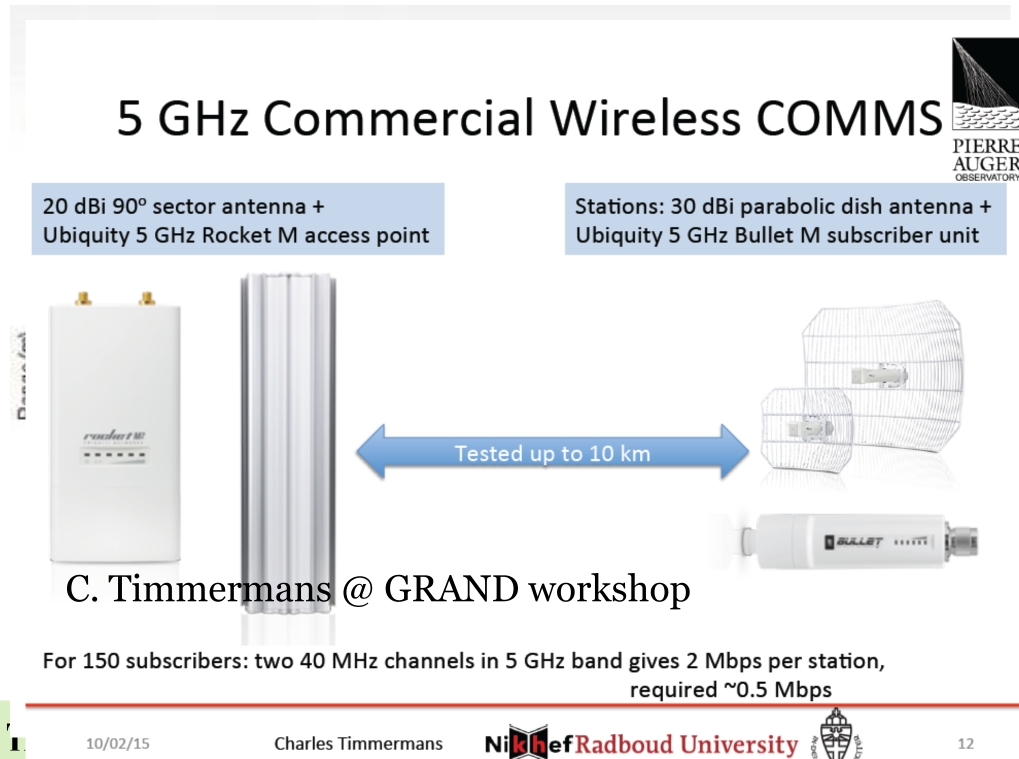
GRAND data format & transfer

- IF we save minimal info: 5x16 = 80 bits per trigger
  - Trig time (32bits <-> 4s)
  - Amplitude (16 bits)
  - Polarization info
    (2 angles: 2x8 bits)
  - Others (ID, monitoring…)
- Assuming <u>trig rate = 100Hz</u>
- 800bytes/antenna/s ⇨ **200MBy/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
  - …





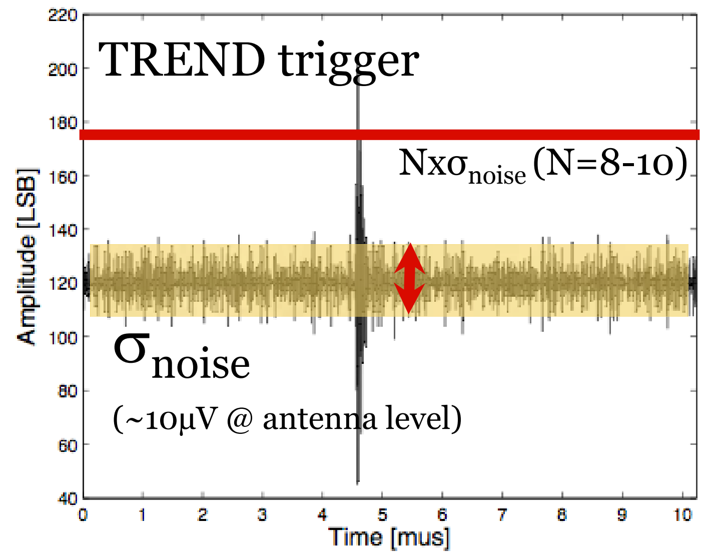
~10$/unit

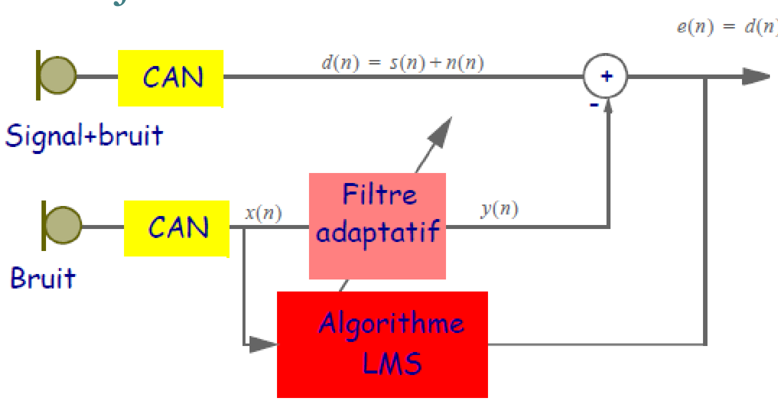


C. Timmermans @ GRAND workshop

GRAND trigger

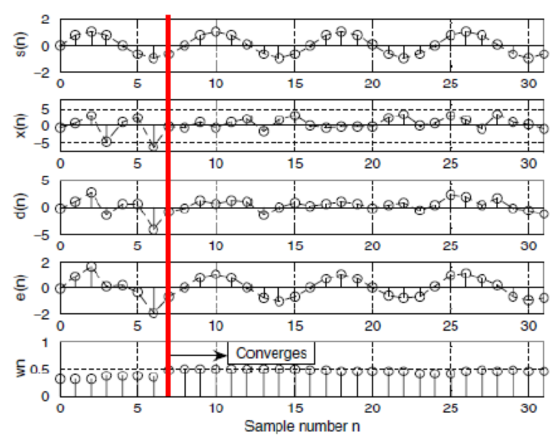
- Investigate online enhanced signal processing @ FPGA level:
  - Very little done on the topic so far… Could be improved because we KNOW expected signal (simulations) AND background (data).
  - Adaptative filter
  - Signal correlation
  - ⇒ 2nd level trigger @ FPGA level
  - ⇒ better threshold, better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





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

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



Signal d'entrée non bruité

Bruit

Signal d'entrée bruité

Signal filtré

Coefficient du filtre

(Temptative) budget for the detection unit

Element	Power consumption	Price
Antenna+Mechanics	-	50$
LNA	~500mW	20$ (3 channels)
Filter	-	30$ (3 channels)
Signal detection (shape selection & trigger)	negligeable	~10$
ADC+FPGA	~150mW	50$
GPS	~100mW	<50$
Com.	~100mW	10$ or ?
Solar pannel	-	50$
Cables, connectors & PCB	-	30$
Total	**~ 1W**	**300$**

300x200000 = 60M$ ➔ 100M$ budget project