

# Status of the ground-based wide-angle gamma-ray and cosmic-ray experiment SCORE / HiSCORE

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Universität Hamburg



Physics motivations

Principle of the array

Status & outlook

# SCORE / HiSCORE aims

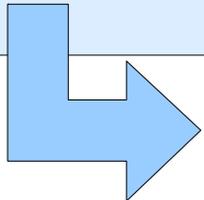
- **SCORE = Study for a Cosmic ORigin Explorer**
- **HiSCORE = Hundred\**i* Square-km Cosmic ORigin Explorer**
- **Cosmic-rays:**  
 $100 \text{ TeV} < E_{\text{CR}} < 1 \text{ EeV}$
- **Ultra-high energy gamma-rays:**  
 $E_{\gamma} > 10 \text{ TeV}$
- **Large area:** 10-100 km<sup>2</sup>
- **Large Field of view:** ~1 sr

Roadmap phase I recommends:

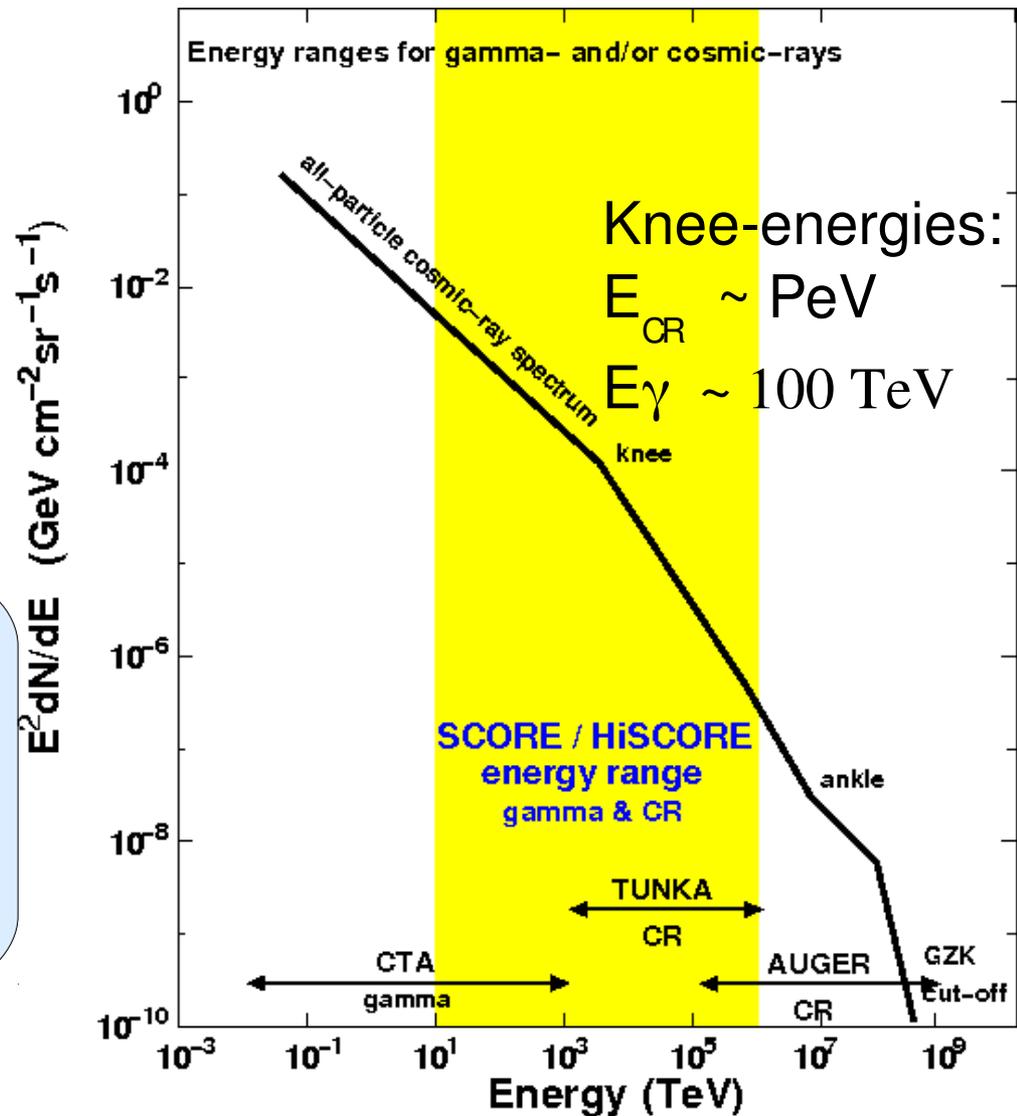
*“development of ground-based wide-angle gamma-ray detectors”*



**ASPERA**



**We propose HiSCORE !**



# Astroparticle Physics @ $E > 10$ TeV

## Gamma-ray Astronomy

- VHE spectra: where do they stop ?
- **Origin of cosmic rays: pevatrons**
- Absorption in IRF & CMB
- Diffuse emission:
  - Galactic plane
  - Local supercluster

## Charged cosmic ray physics

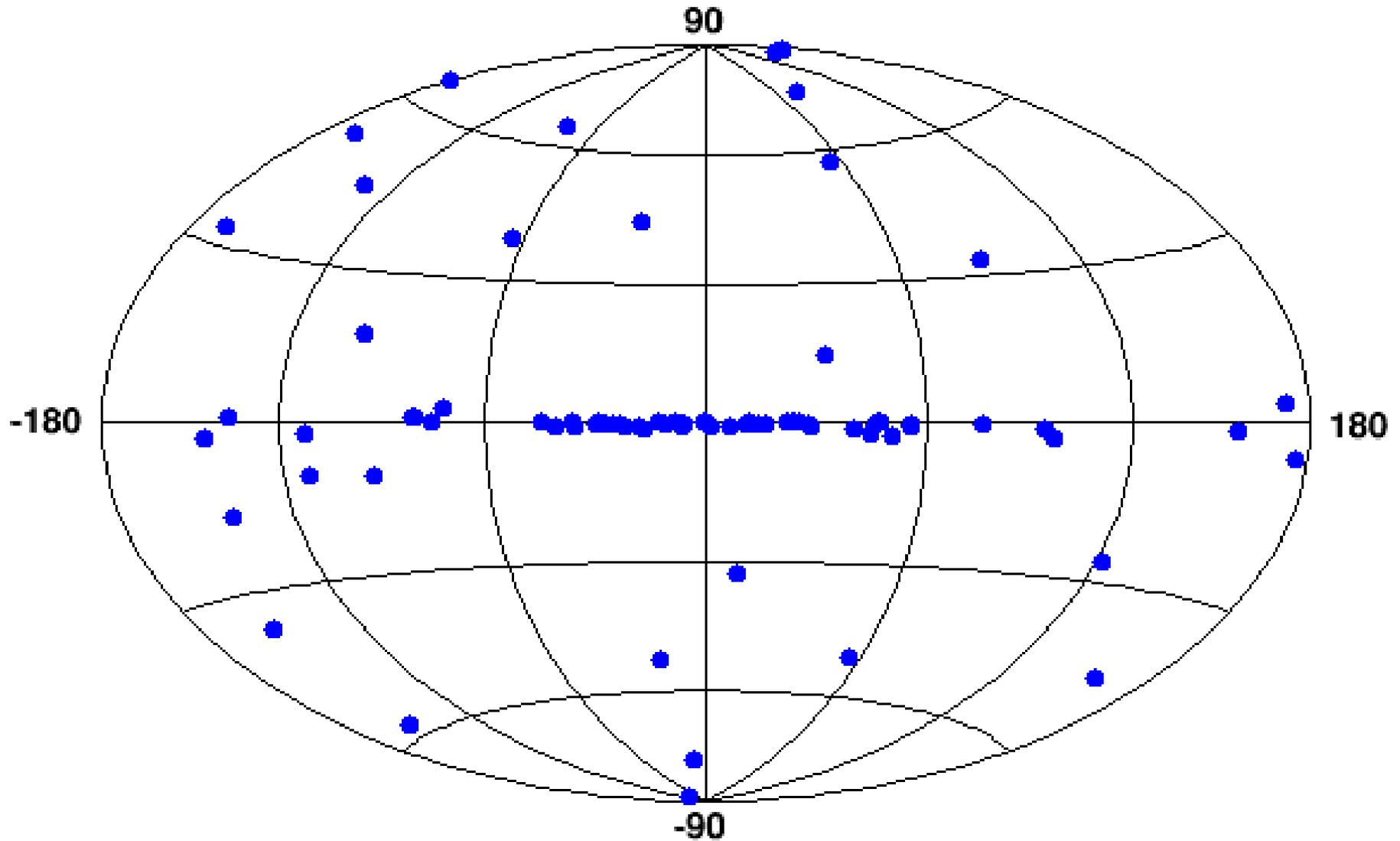
- Composition / anisotropies
- Sub-knee to pre-ankle

## Particle physics beyond LHC

- Axion / photon conversion
- Hidden photon / photon oscillations
- Lorentz invariance violation
- **pp cross-section measurements**
- Quark-gluon plasma

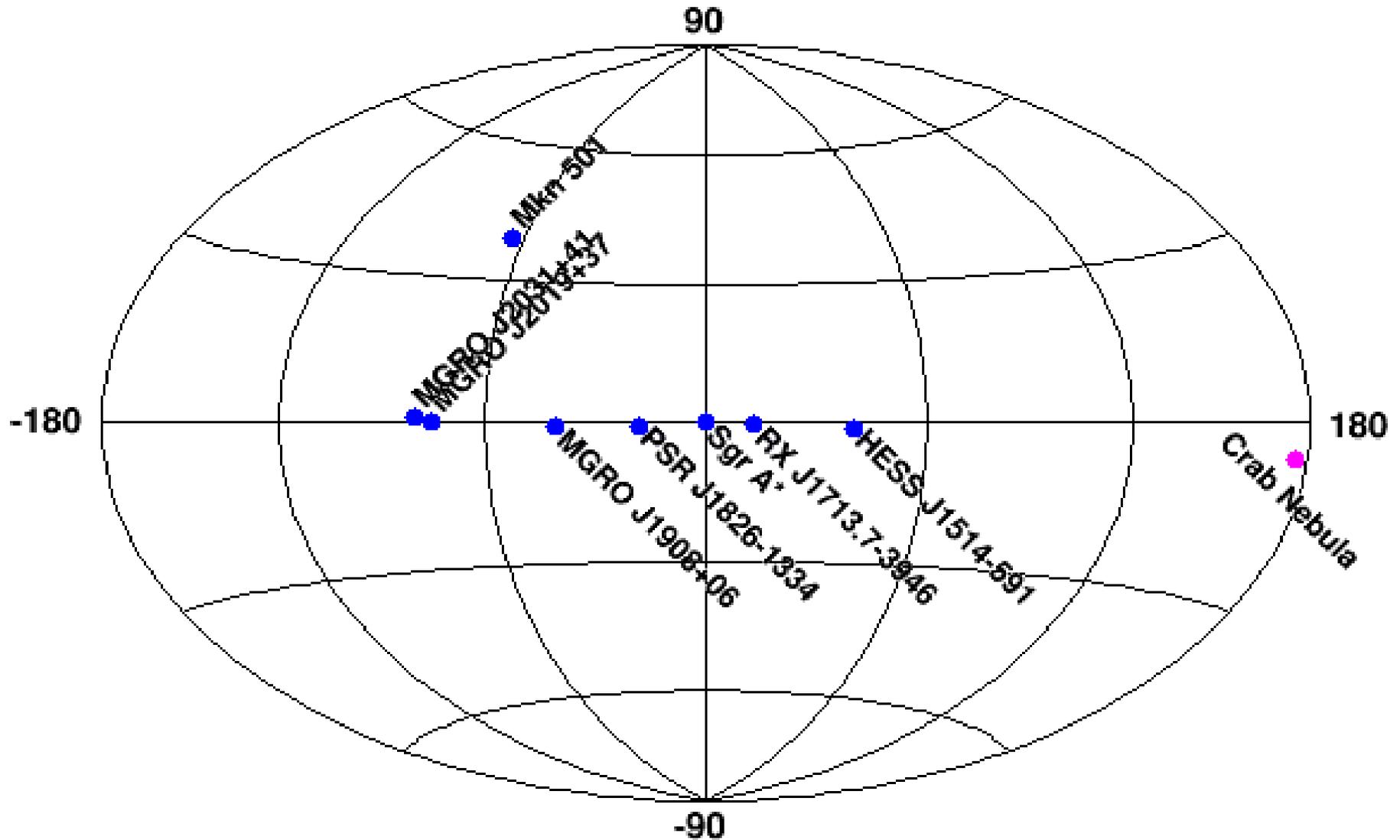
# Gamma-Ray Sky, $E > 100\text{GeV}$

VHE gamma-ray sky 2009



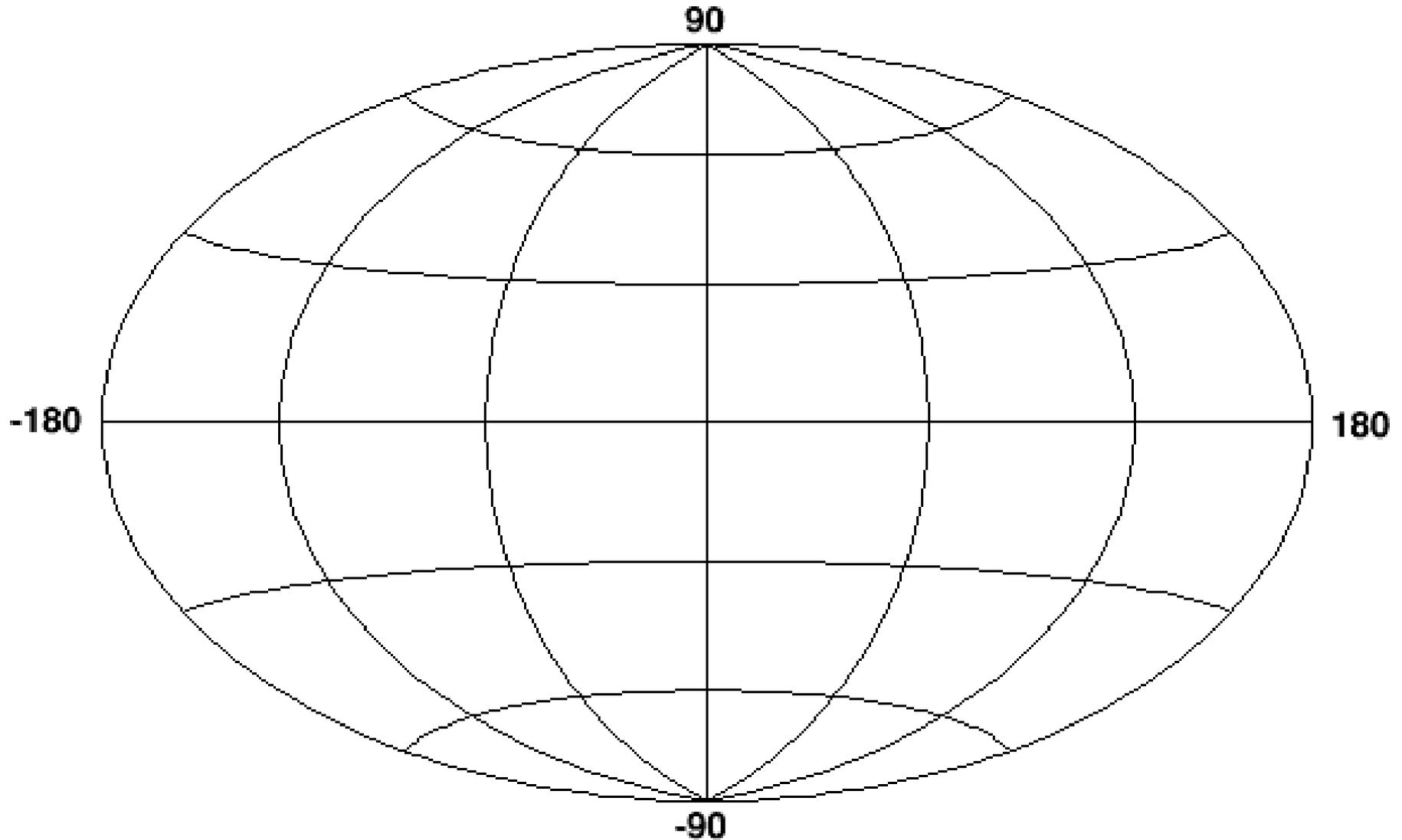
# Gamma-Ray Sky, $E > 10 \text{ TeV}$

UHE Gamma-Ray Sky ( $S > 5 \sigma$ ,  $E > 10 \text{ TeV}$ ), May 2009

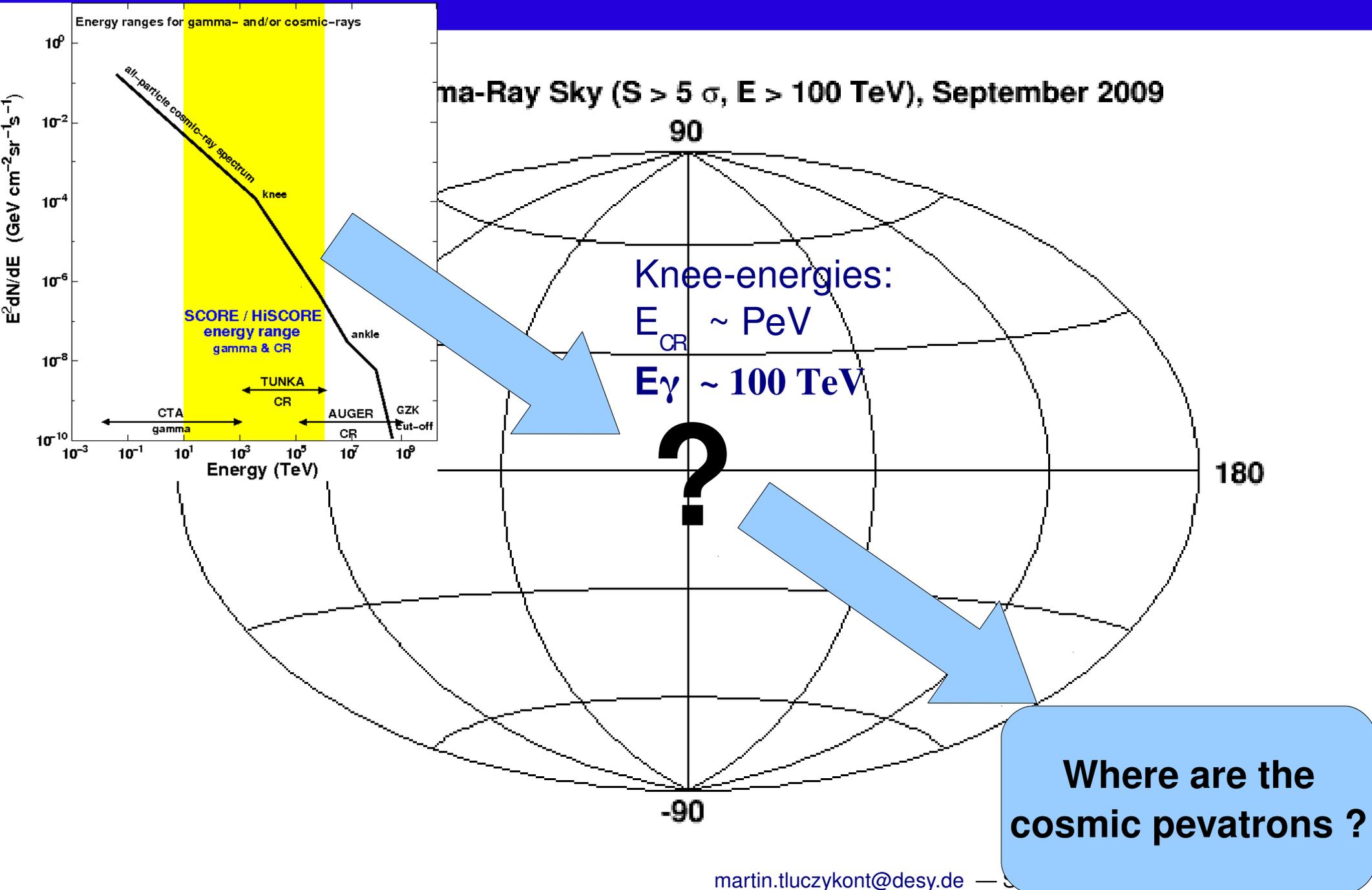


# Gamma-Ray Sky, $E > 100 \text{ TeV}$

UHE Gamma-Ray Sky ( $S > 5 \sigma$ ,  $E > 100 \text{ TeV}$ ), September 2009

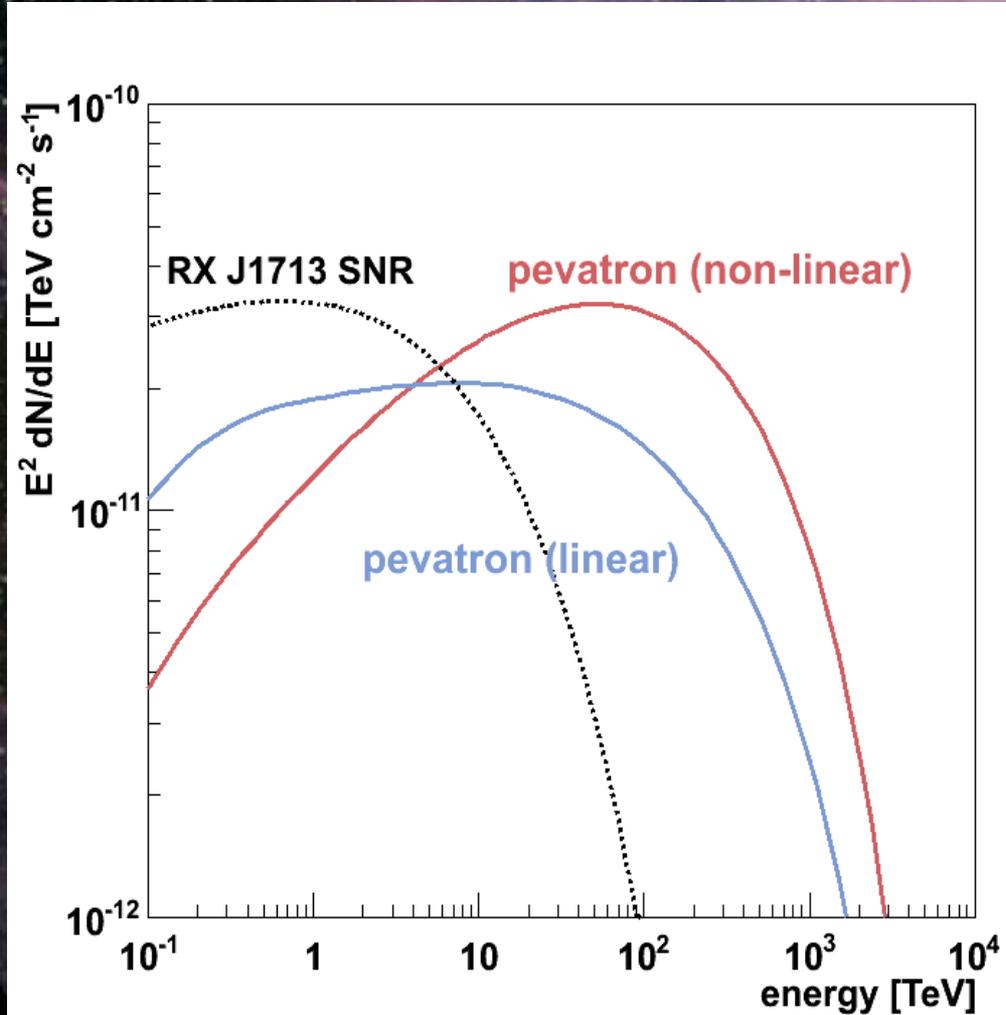


# Gamma-Ray Sky, $E > 100 \text{ TeV}$



# Where are the cosmic pevatrons ?

The main goal of SCORE



All known supernova remnants:  
cut-off energy too low

Find Cosmic accelerators:

- UHE:  
IC in Klein-Nishina regime
- hard spectra beyond 10 TeV  
must be hadronic !

Long acceleration times:  
expect extended emission

Pevatrons so far unrevealed !



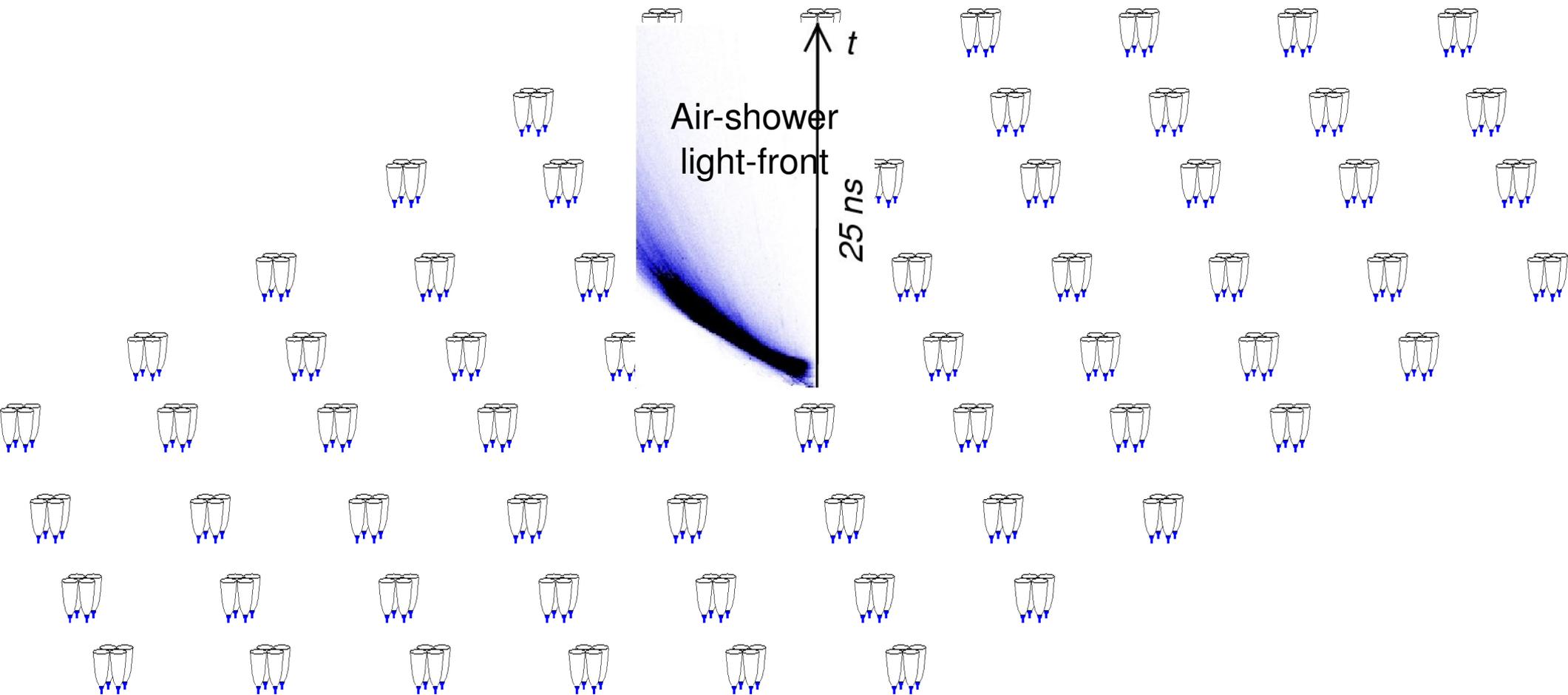
# The SCORE principle

- Ultra-High energy regime: **need large effective area !**
- Imaging ACTs:  $> 10000$  channels /  $\text{km}^2$
- **Non-imaging shower-front sampling**  
SCORE:  $< 200$  channels /  $\text{km}^2$



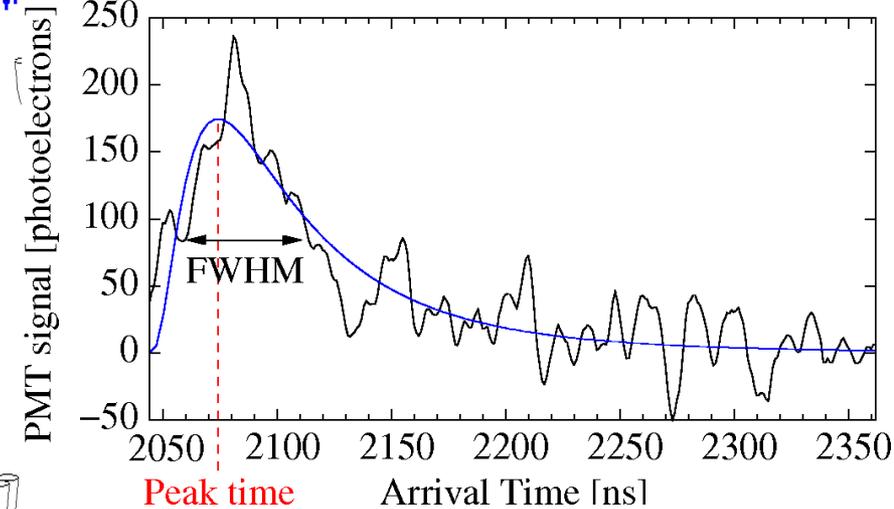
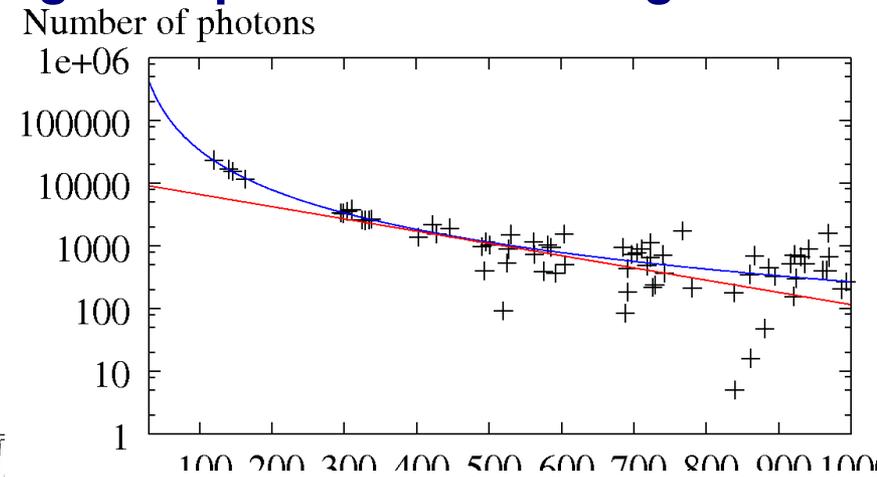
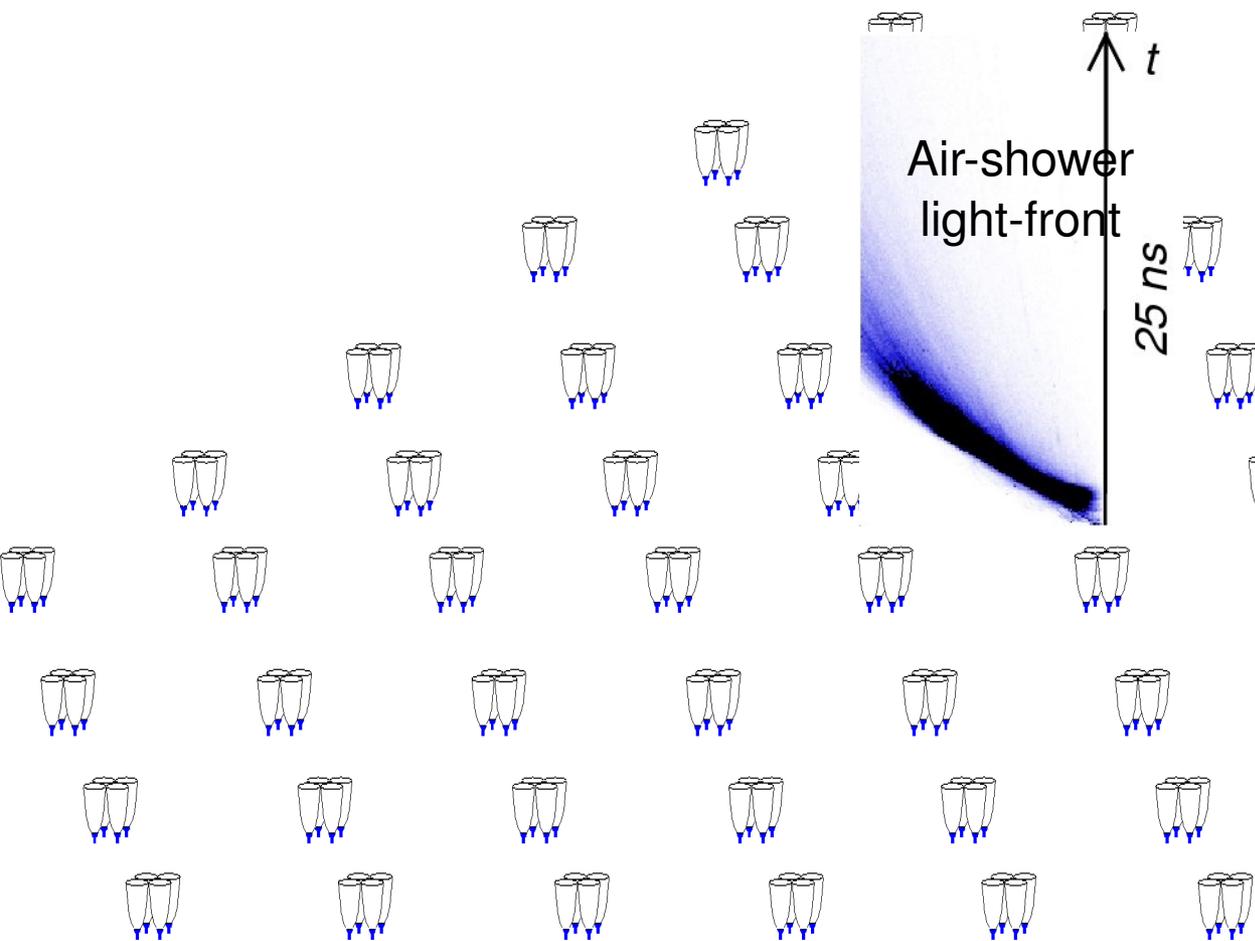
# The SCORE principle

- Ultra-High energy regime: **need large effective area !**
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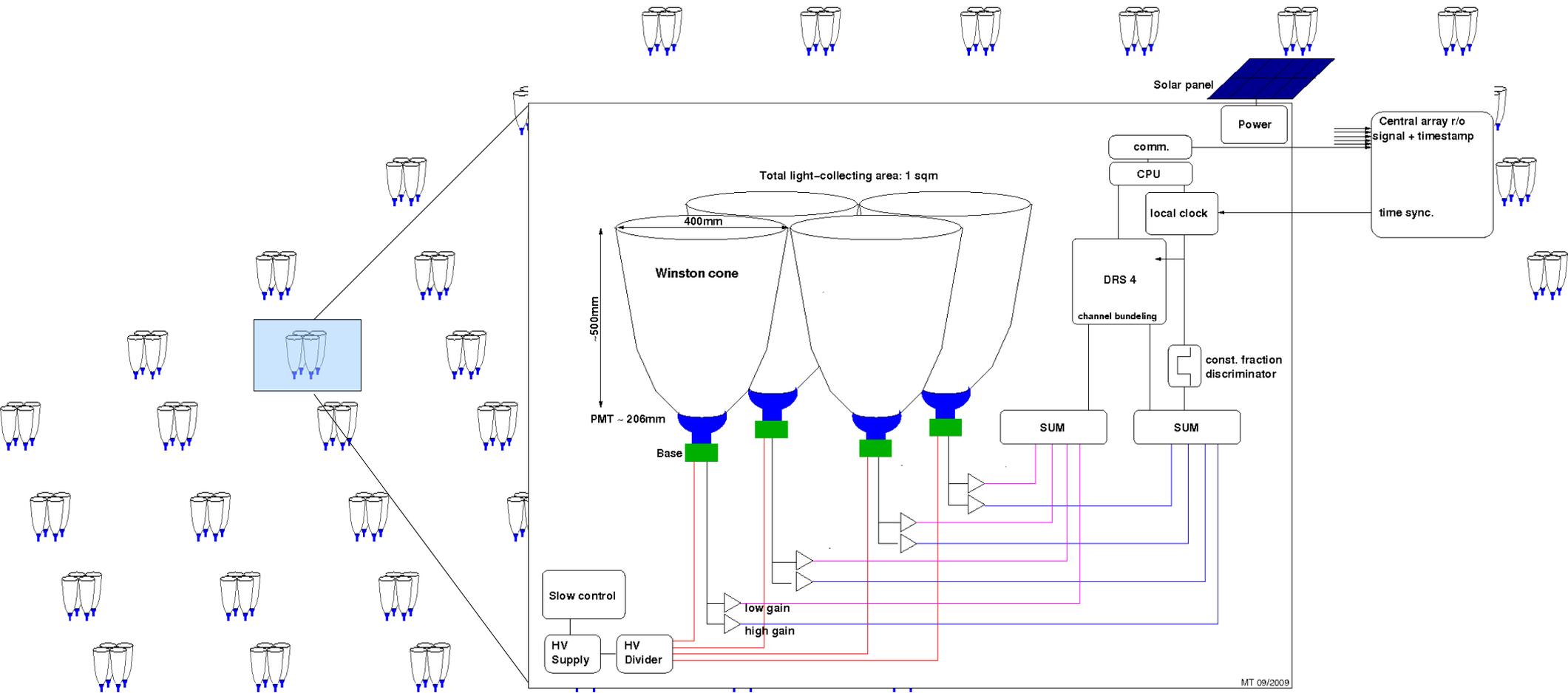
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# The SCORE principle

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# Simulation

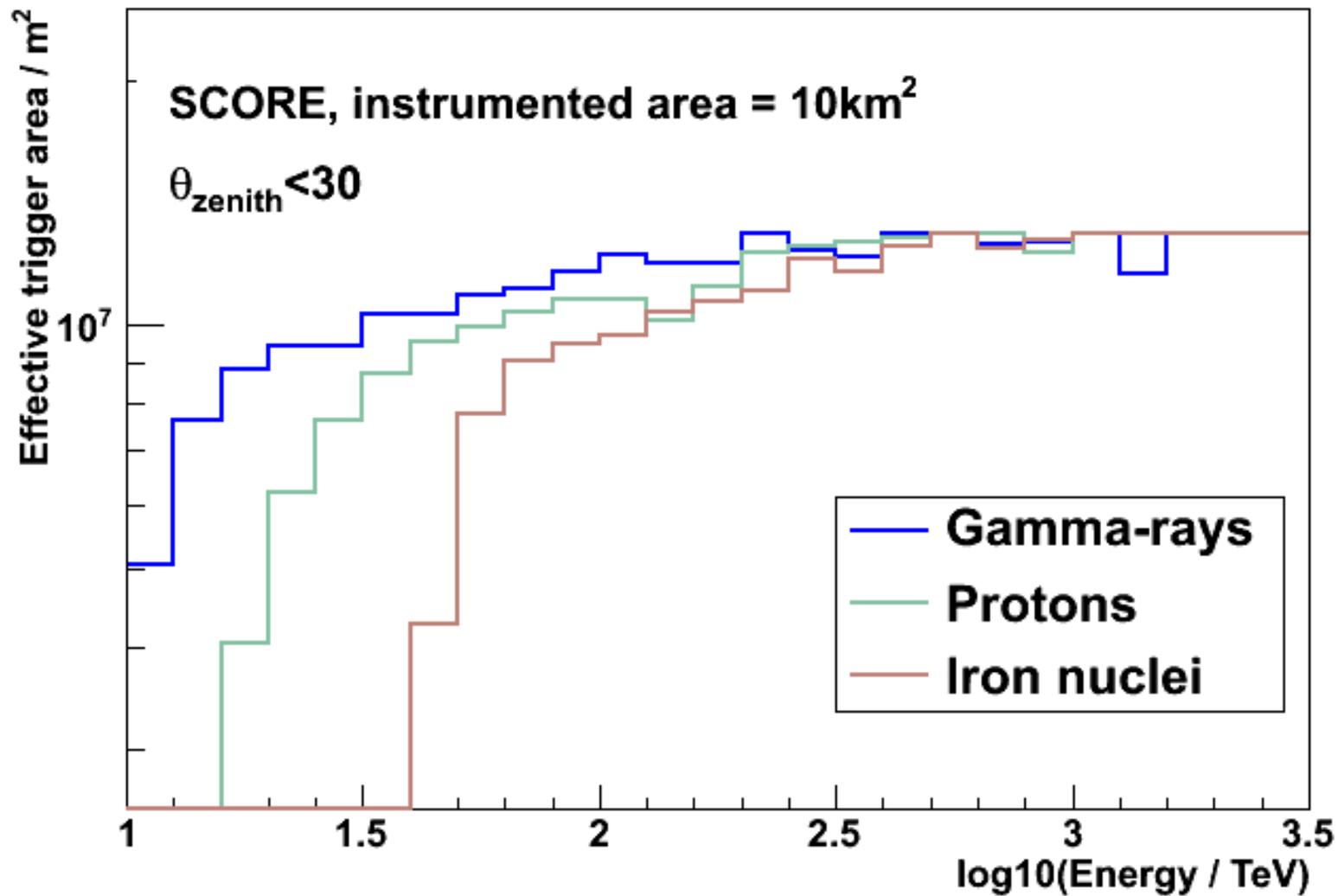
## **Air-shower simulation CORSIKA 6735 [1]:**

- using the hadronic interaction model Gheisha [2]
- including the iact Cherenkov photon package by [3]

## **Full detector simulation – sim\_score [5]:**

- using iact package I/O routines, provided by [3]
- Winston cone acceptance included by ray-tracing simulation
- PMT quantum efficiency included (Electron Tubes 8inch PMT data)
- PMT signal pulse-shape parameterization [4]
- Next neighbour trigger simulation –  $1\mu\text{s}$  coincidence window
- Night-sky background (including pulse shaping), added to signals

# Effective trigger area



# Performance

## Shower core

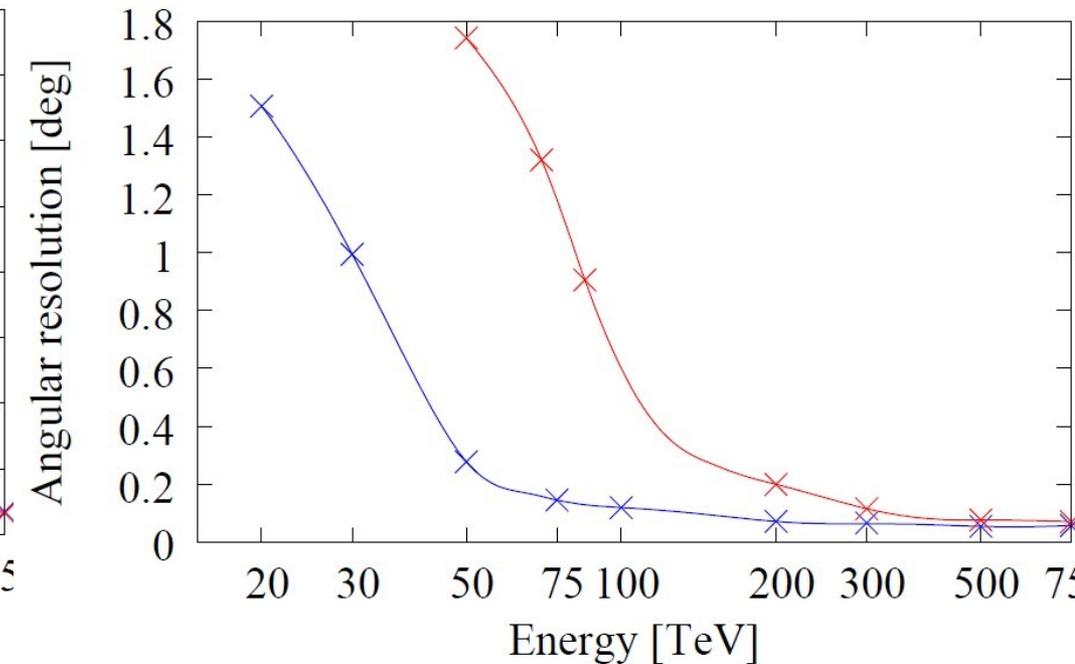
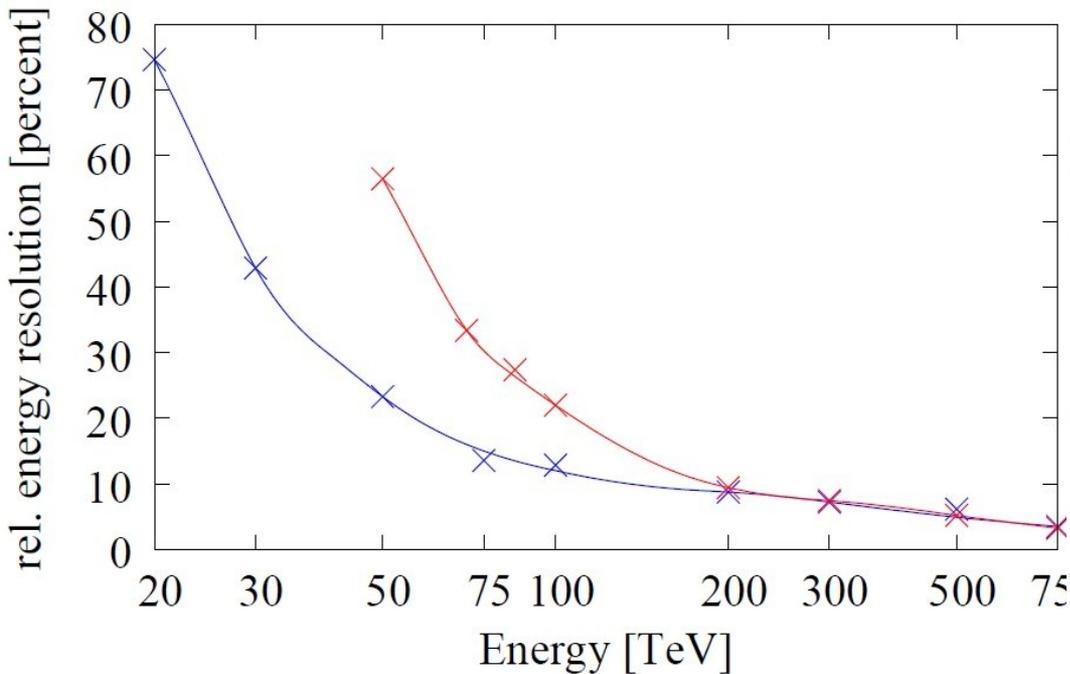
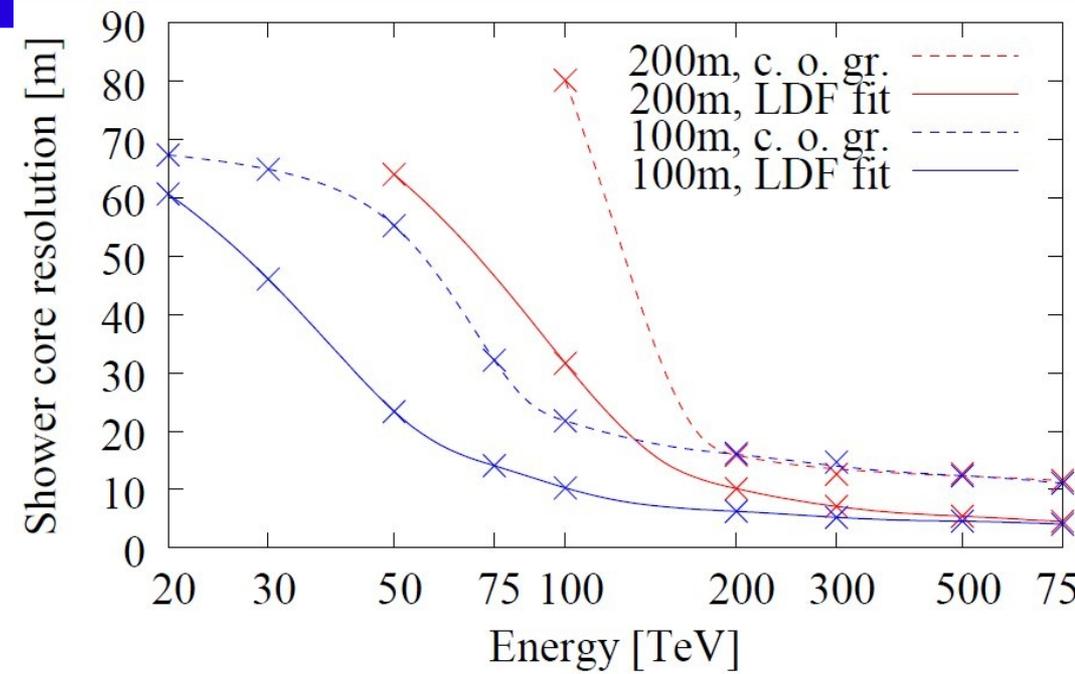
Trivial method: center-of-gravity of light distribution.  
Improved method: 2D-fit of lateral density function to station data

## Primary energy

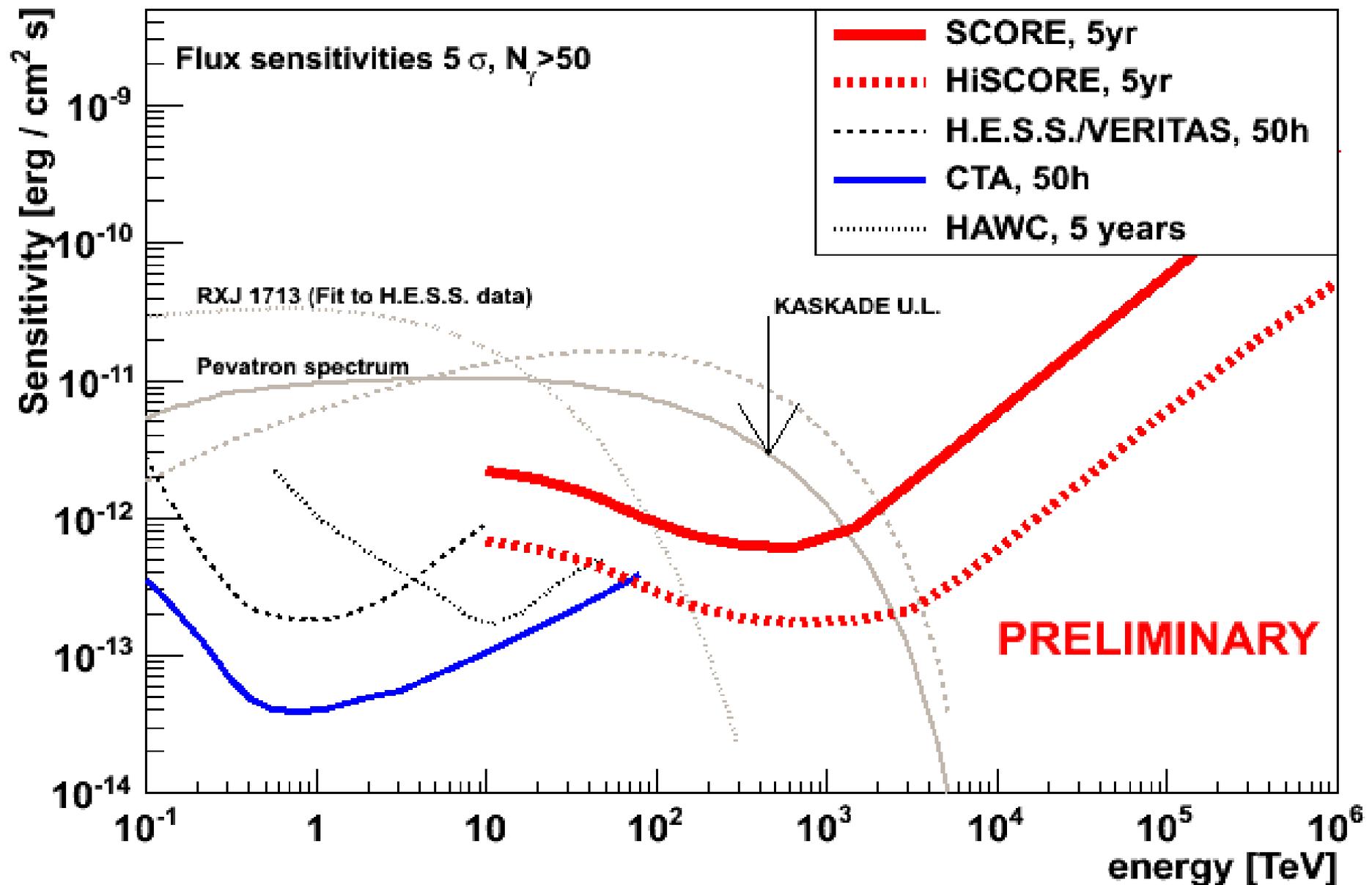
The observed photon-density on the ground is proportional to the energy of the primary particle.

## Primary direction

2D-fit of the sum of a parabola and a plane to the measured arrival times. Same results when including a time-jitter of up to 3ns.



# SCORE First Simulation Results



# Status

- Full detector simulation and basic reconstruction completed
- Current software activities:
  - Testing different layouts & studying combination w/ IACTs
  - Optimizing reconstruction and simulation (e.g. afterpulsing)
- Studies of first Hardware components in progress
- Small-scale prototype in Hamburg (~4 stations)
- Large-scale prototype in Siberia
  - Plan cooperation with Tunka group, MSU Russia
  - Planning construction of **~0.5 km<sup>2</sup> array in Siberia**
  - Great benefit from Tunka expertise and site-infrastructure
  - Synergies with Tunka-array and planned Tunka  $\mu$ -detector

# Summary

- **Many physics cases beyond 10 TeV primary energy**
- **ASPERA Roadmap phase I:**  
recommends a wide-angle ground-based gamma-ray experiment
- **We propose SCORE / HiSCORE**  
opening up the last remaining Gamma-ray observation window !
- **Simulation / R&D in process**
- **Further ideas:**  
Combination with radio / scintil. / imaging technique under study
- **See you @ COSPAR – Publication in preparation**
- **Cooperation is welcome**

# References

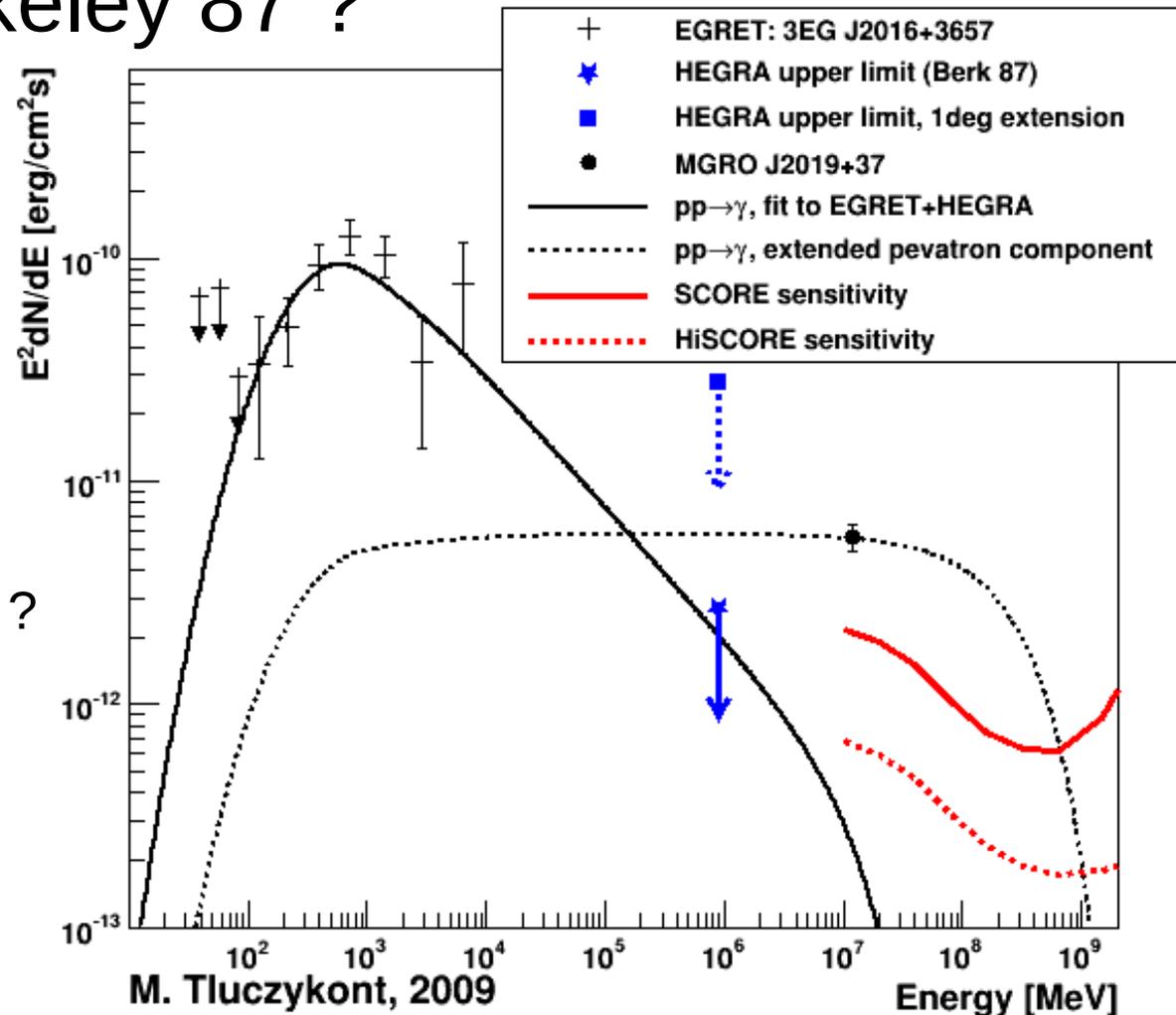
- [1] D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz, and T. Thouw, Report **FZKA 6019** (1998), Forschungszentrum Karlsruhe; available from <http://www-ik.fzk.de/~heck/publications>
- [2] H. Fesefeldt, Report **PITHA-85/02** (1985), RWTH Aachen
- [3] K. Bernlöhner (2008), astrop-ph preprint, arXiv:0808.2253
- [4] V. Henke (1994), Diploma thesis, University of Hamburg
- [5] **M. Tluczykont, T. Kneiske, D. Hampf & D. Horns (2009), to appear in Proc. of the ICRC 2009, arXiv e-print (arXiv:0909.0445v1)**
- [6] **D. Hampf, M. Tluczykont & D. Horns (2009), to appear in Proc. Of the ICRC 2009, arXiv e-print (arXiv:0909.0663v1)**
- [7] J.R. Hörandel, Astropart. Phys., 19, 193 (2003)

# Backup

# Pevatron emission from Cygnus ?

## MGROJ2019+37 & Berkeley 87 ?

- Composite Milagro signal  
**Diffuse + unresolved**
- HEGRA upper limit  
(converted for extension)
- HE signal associated to pulsar ?  
Fermi: J2020.8+3649  
EGRET: 3EG J2021+3716



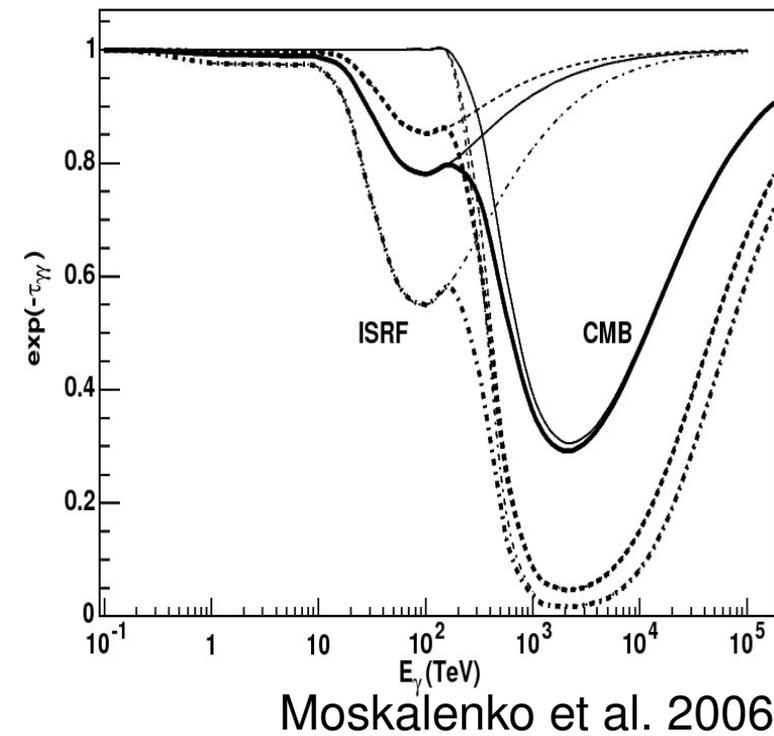
- ➔ Milagro signal might be dominated by extended pevatron emission !
- ➔ SCORE: resolve emission from 10 TeV – 1 PeV

# Hardware Prototyping / Testing

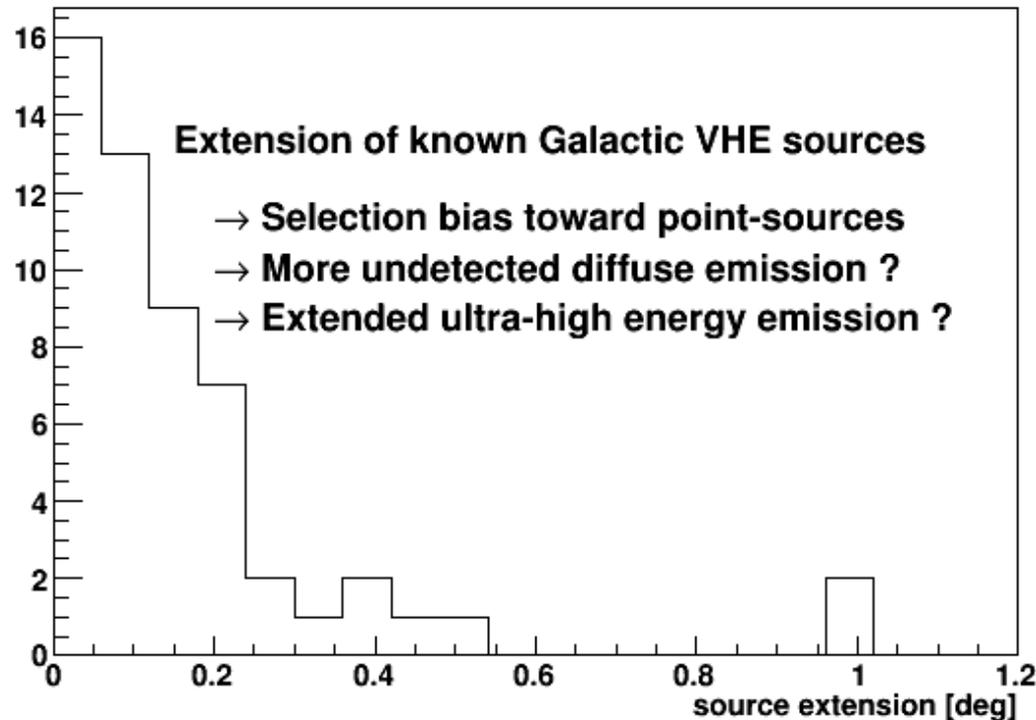
- **Winston Cones**
  - Aluminum sheet prototype construction done
  - Use UP4300 instead – Reflectivity measurement looks good
- **PMTs:** 12 x 206mm Electron Tubes  
(from MPPMU via Eckart and Ina, thanks !)
- **Readout:** DRS4 chip developing board
- Currently building PMT test bed
- Planning first prototype deployment on DESY site:  
closed stations w/ scintillator, for **testing electronics**
- NSB measurement in Australia  
RP580 PMTs, discriminator + ADC/scaler for NSB photon count

# Propagation: Galactic Absorption & CMB

- $e^+e^-$  pair production: Interstellar radiation field (ISRF) and CMB
- **estimate ISRF density**
- CMB well known: **distance estimate?**
- Weakening of absorption by:
  - ➔ **Photon / axion conversion** in Galactic Magnetic field
  - ➔ **Photon / hidden photon oscillation**
  - ➔ **Lorentz invariance violation** (modification of  $e^+e^-$  threshold)



# Diffuse / extended emission



- Many Galactic objects are extended
- Extended emission: more background, less sensitivity
- Expect so far undetected extended sources !

## The Galactic plane

- Production of gamma-rays from CR-gas interaction
- Extending the energy range covered

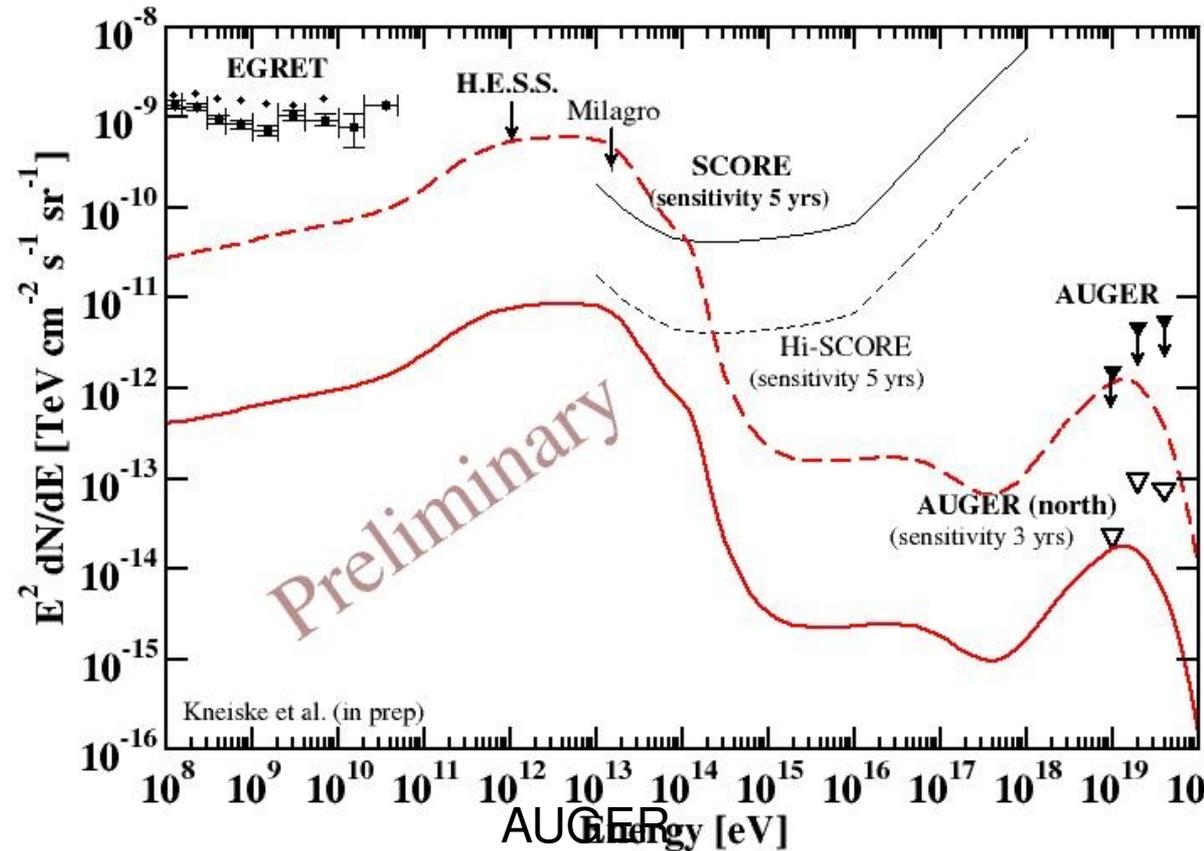
# Local Supercluster and UHECRs

- UHECRs

confined in **local supercluster**

**Expect diffuse emission**

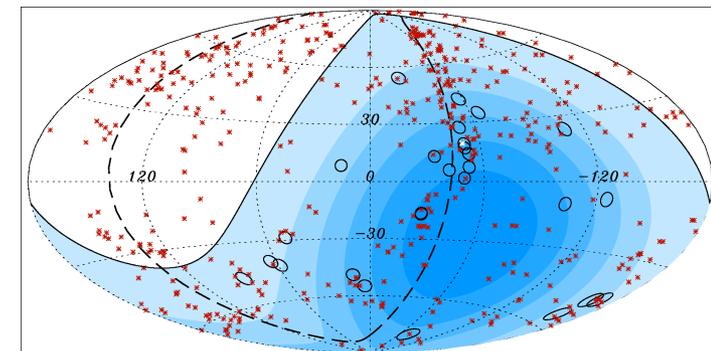
*See T. Kneiske, Lodz 2009*



- **Point-sources from AGN ?**

- IC Pair-cascading

- Haloes ?



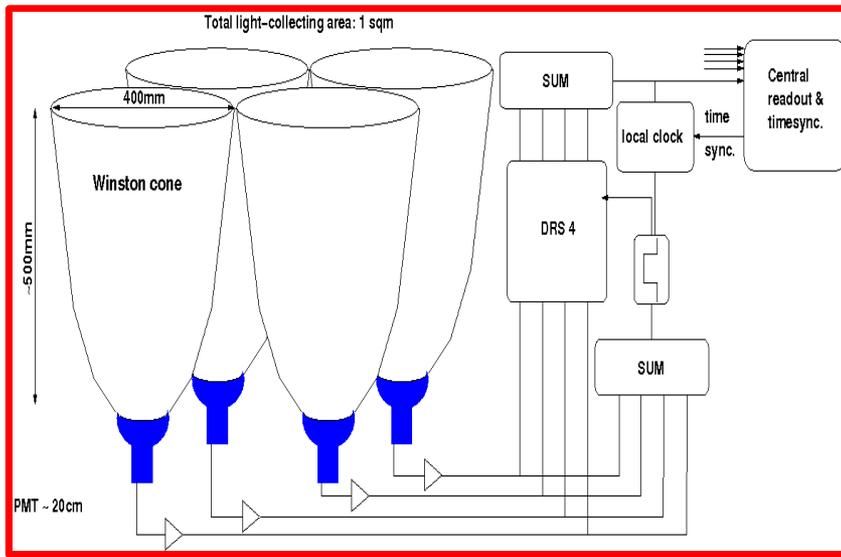
# Monopoles

- Monopoles emit a lot of Cherenkov light
- Study by Gerrit Spengler (Berlin): Monopole search with H.E.S.S.
- Might reach AMANDA sensitivity with CTA
- Even better with SCORE ?

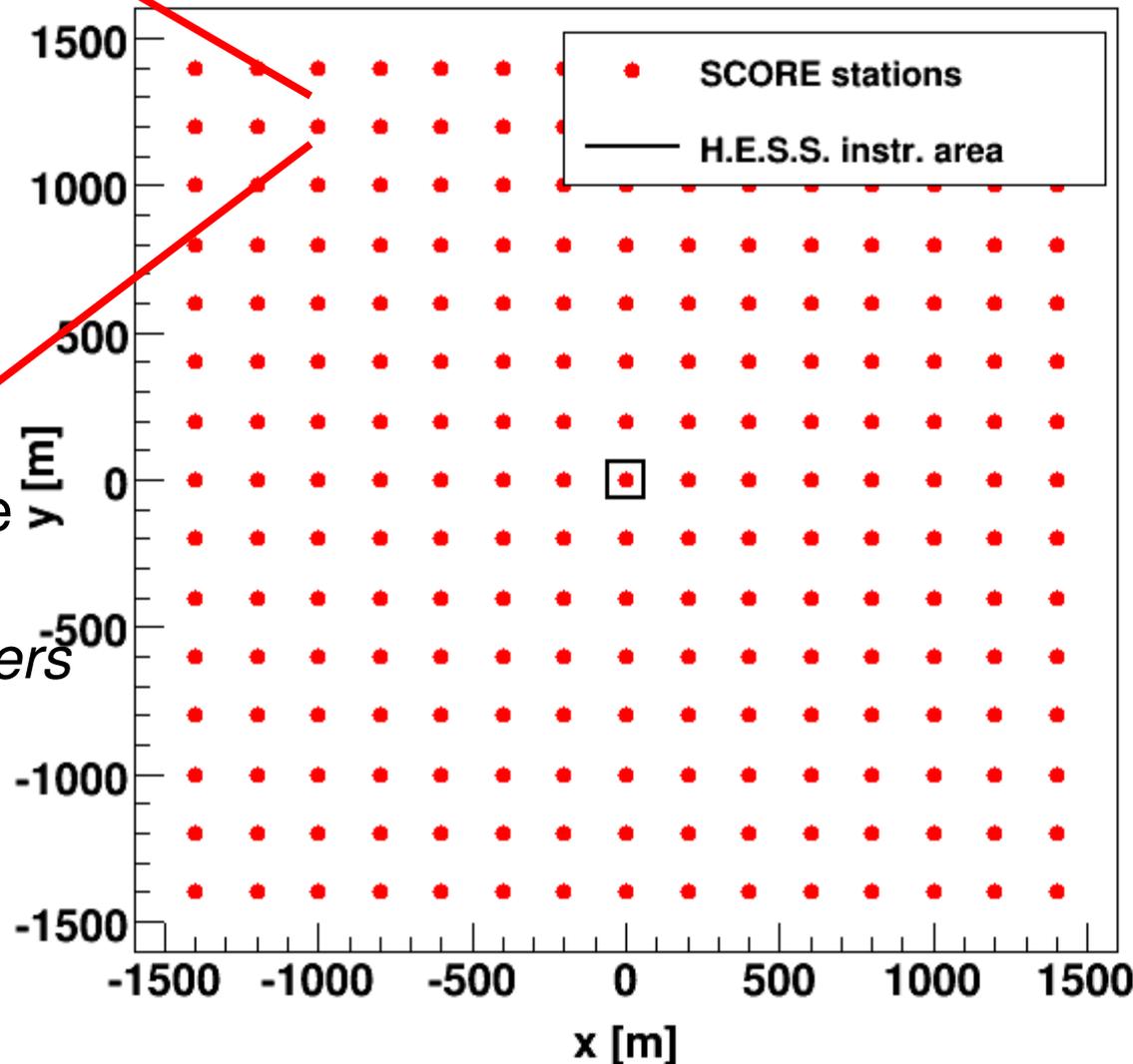
# Funding

- **Existing funds of Group of Prof. Horns:  
hardware prototyping (SCORE, CTA)**
- **Waiting for reply from DFG:**  
*“Initiation and intensification of international cooperation”*  
Application by Hamburg/MSU, December 2009  
Travel funds Germany ↔ Russia
- **Planning:**
  - Further application to DFG for Hardware (Summer 2010)
  - Application to EU for Positions & Hardware (October 2010)
- **Envisaged:**
  - Application to BMBF (?)
  - Application for EU Instrumentation / Infrastructure

# SCORE Detector Array

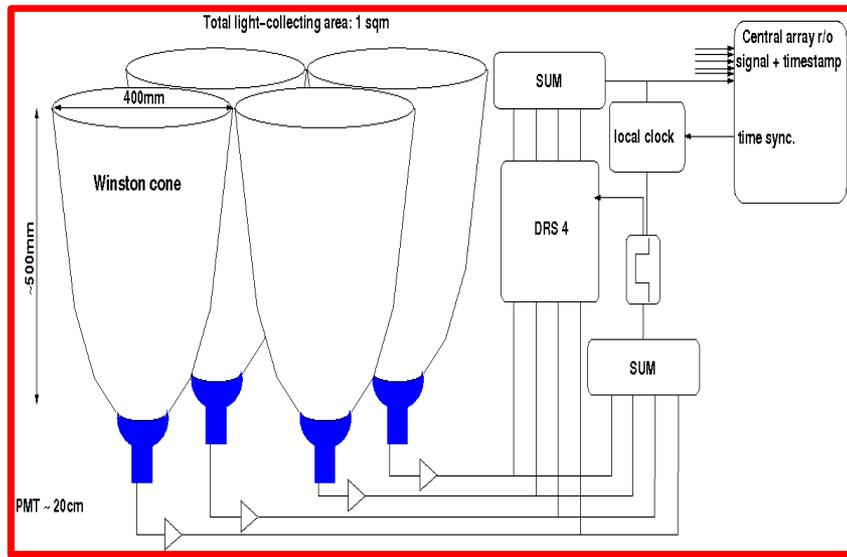


Simulated layout A

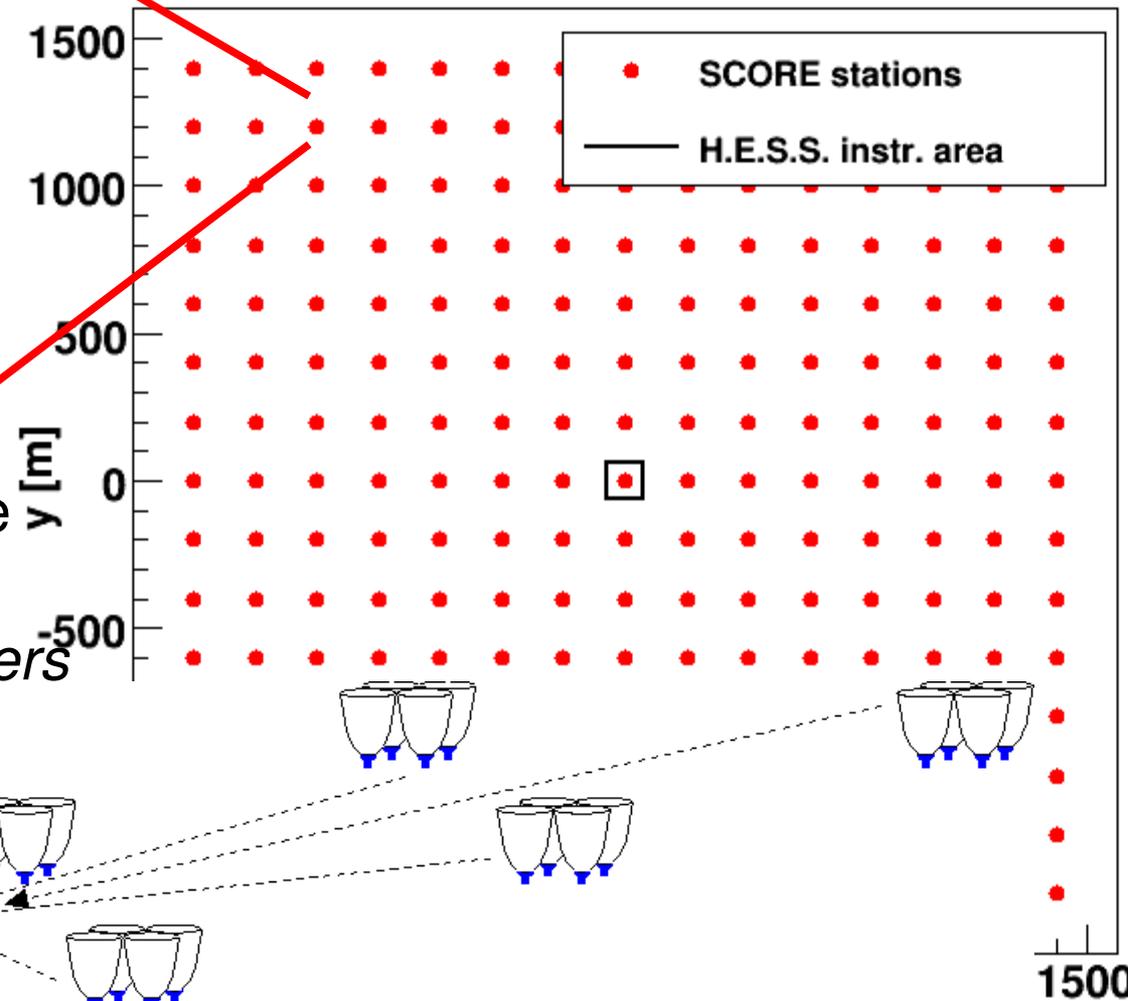


Station trigger: 4-channel coincidence  
Array trigger: 2-station coincidence  
Distribute over sub-array *cluster triggers*

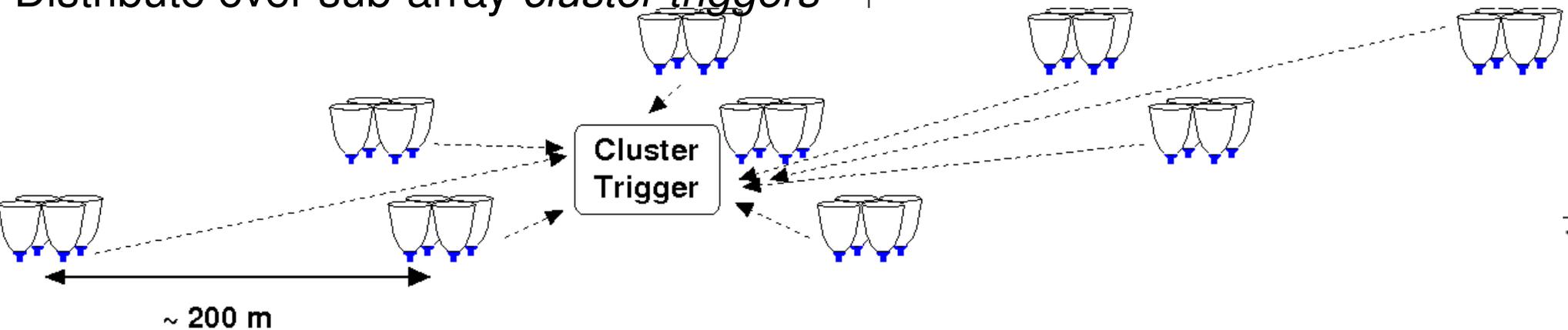
# SCORE Detector Array



Simulated layout A



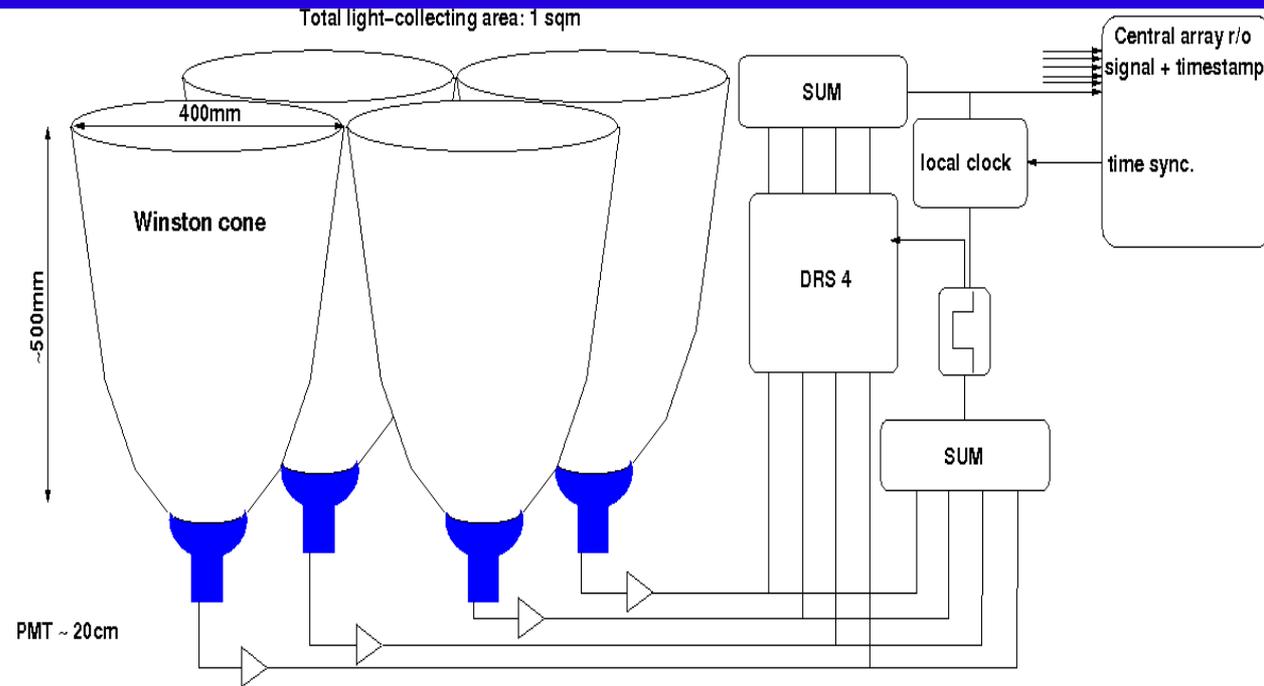
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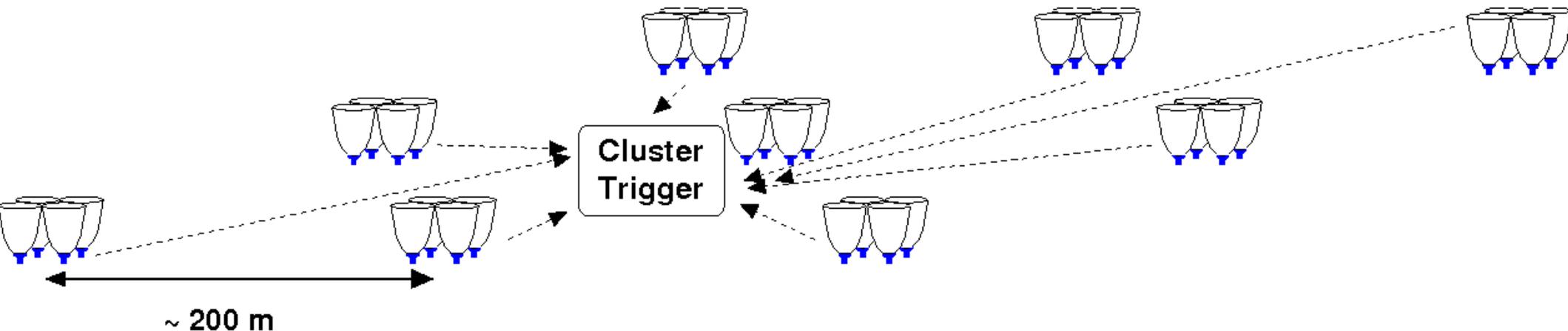
# Trigger levels

## 1) Local station trigger:

- multi-PMT station
- 4-fold local coincidence ( $\Delta t = 1\text{ns}$ )

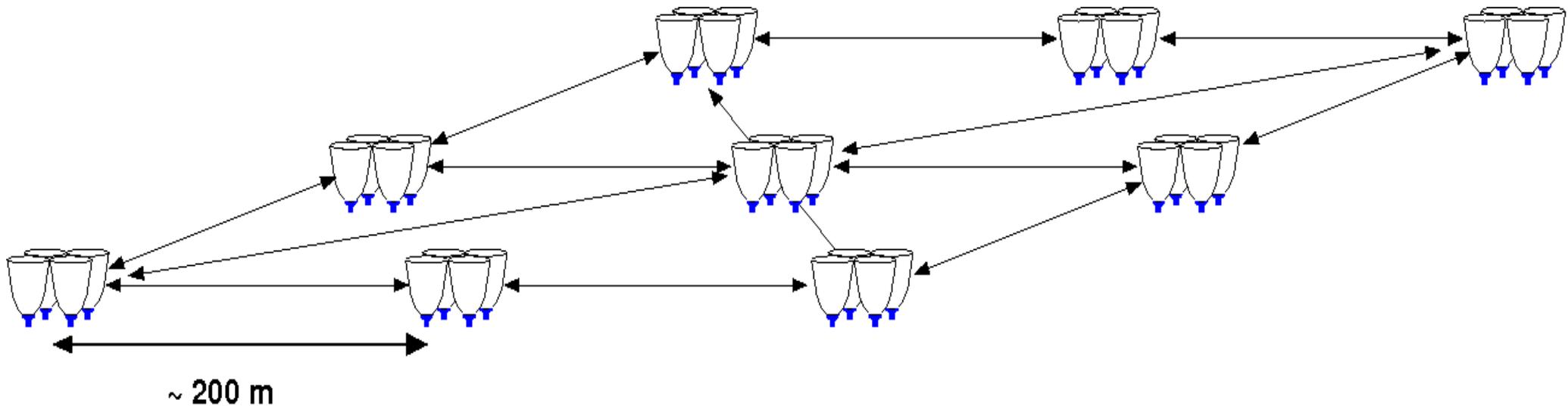


## 2) Array trigger: next-neighbour station trigger ( $\Delta t = 1\mu\text{s}$ )



# Smart Array Trigger

- Each station “knows” neighbours
- Readout triggered stations + next N stations  
(use more than triggered stations in reconstruction)



# Time Synchronization

- Need  $< 5\text{ns}$  timestamp accuracy
- GPS is no option:  $10\text{ ns}$
- Optical fibers: expensive
- Alternative: **Lightsource synchronization:**
  - Isotropic lightsource at central array readout
  - Need short rise time of light-pulse ( $\sim 1\text{ns}$ )
  - Small mirrors on each cone: deflect light on PMT



# Time Synchronization

## Light source synchronization sequence:

$T = T_s$  Central sends synchronization “warning”

And central synchronization time  $T_s$

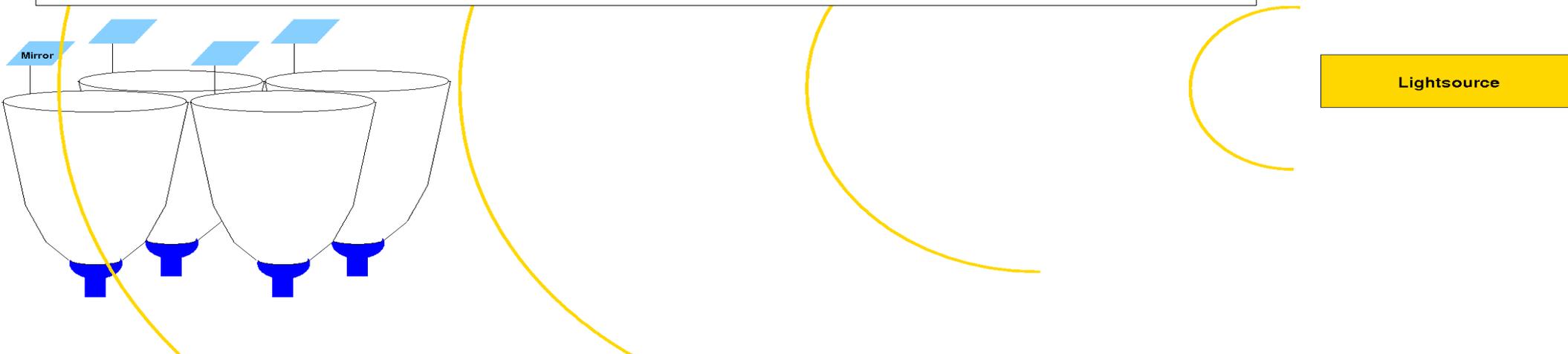
Station switches to “wait for sync”

$T = T_s + 10\text{ns}$  Send light-pulse

Station triggered by light pulse

Synchronize local clock to  $T_s + 10\text{ns} + d/c$

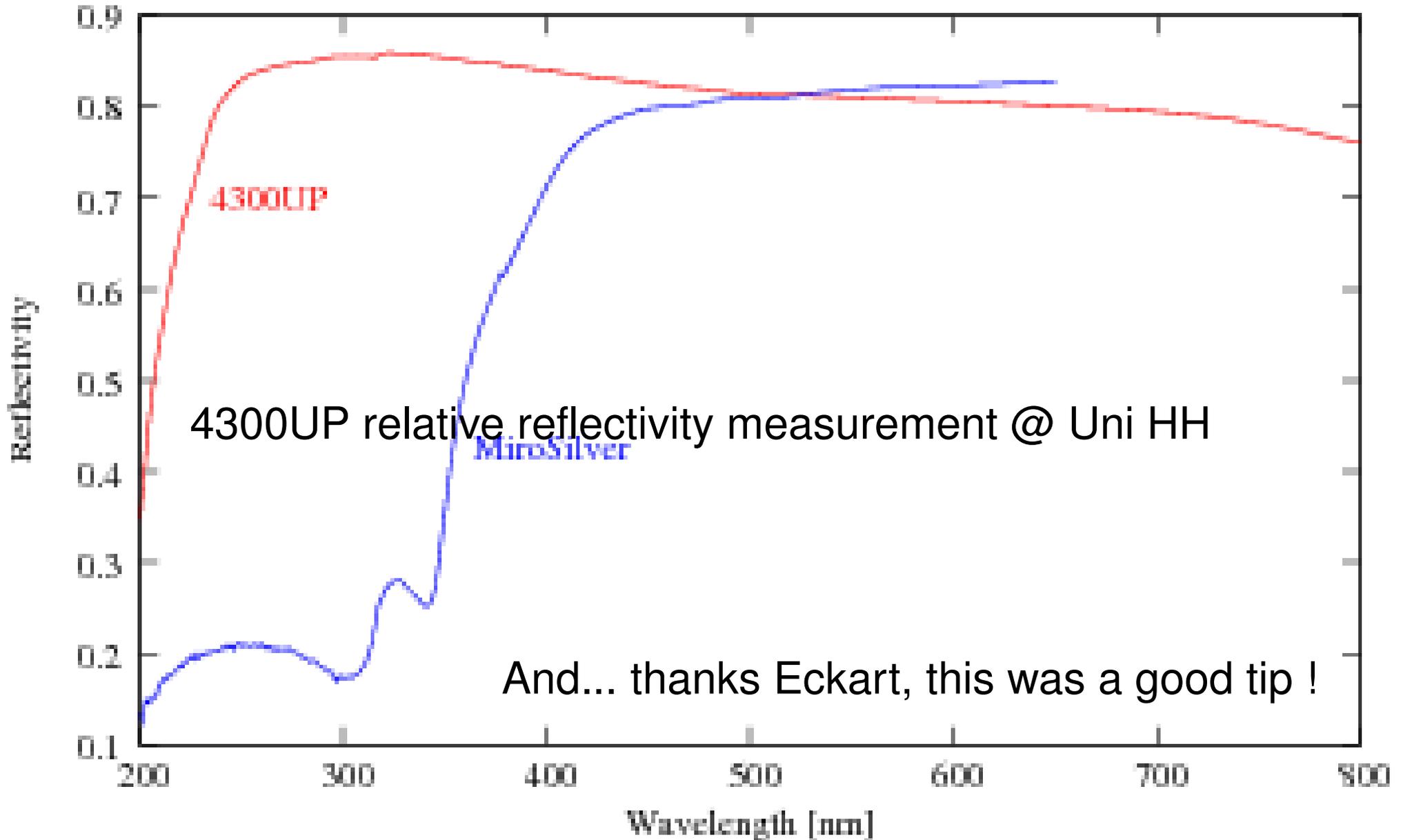
Dead-time:  $10\text{ns} + \text{synchronization length}$



# SCORE Detector Array

- Layout A:
  - Station spacing 200 m
  - Station area  $\sim 1 \text{ m}^2$  (Cone entrance)
  - Field of view 0.85 sterad ( $30^\circ$  half opening angle)
- Currently working on different layouts:
  - Variation of station density and area
  - Station clustering (e.g. array of dense 3x3 clusters)

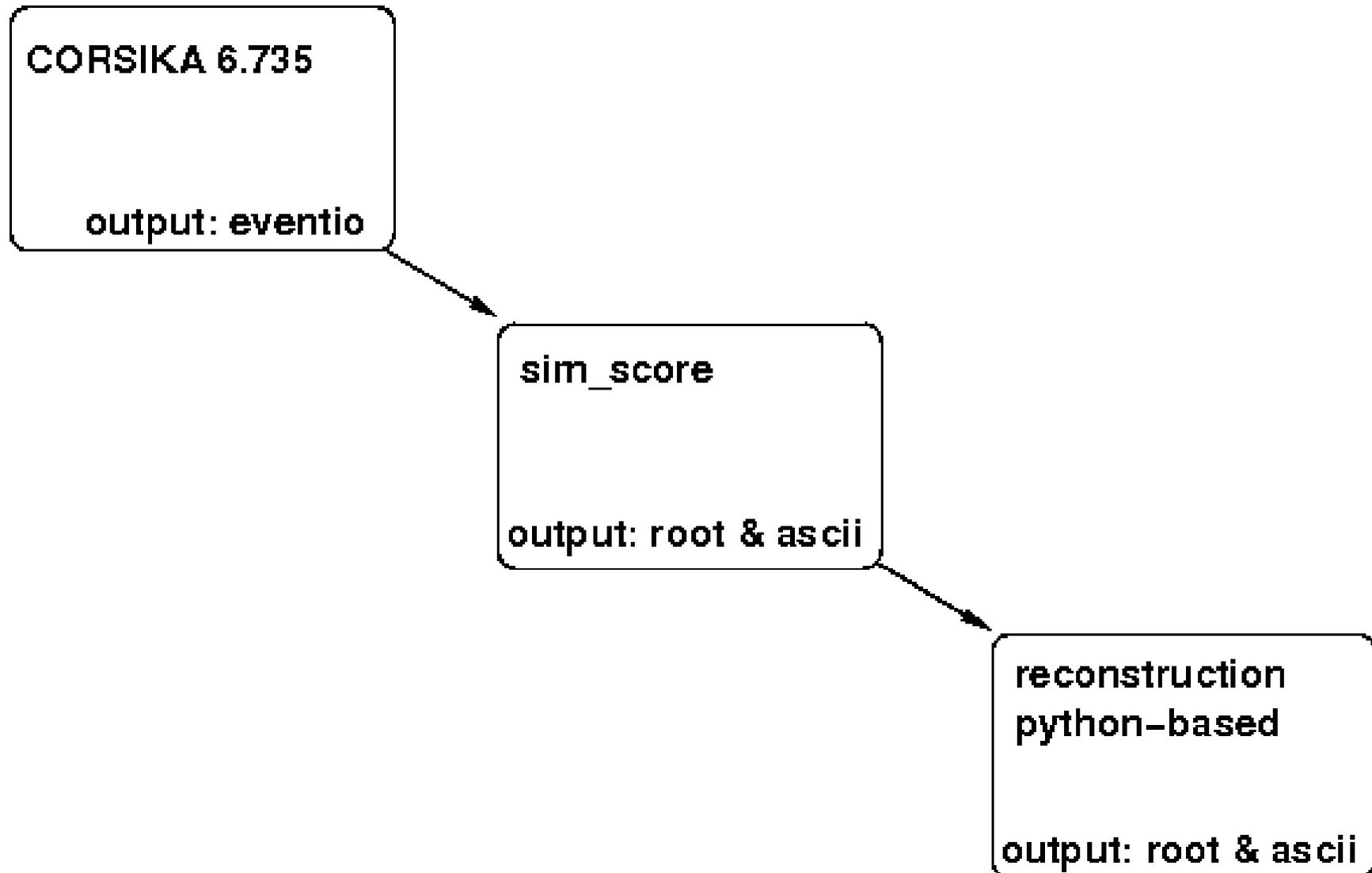
# Hardware Prototyping / Testing



# SCORE Detector Simulation

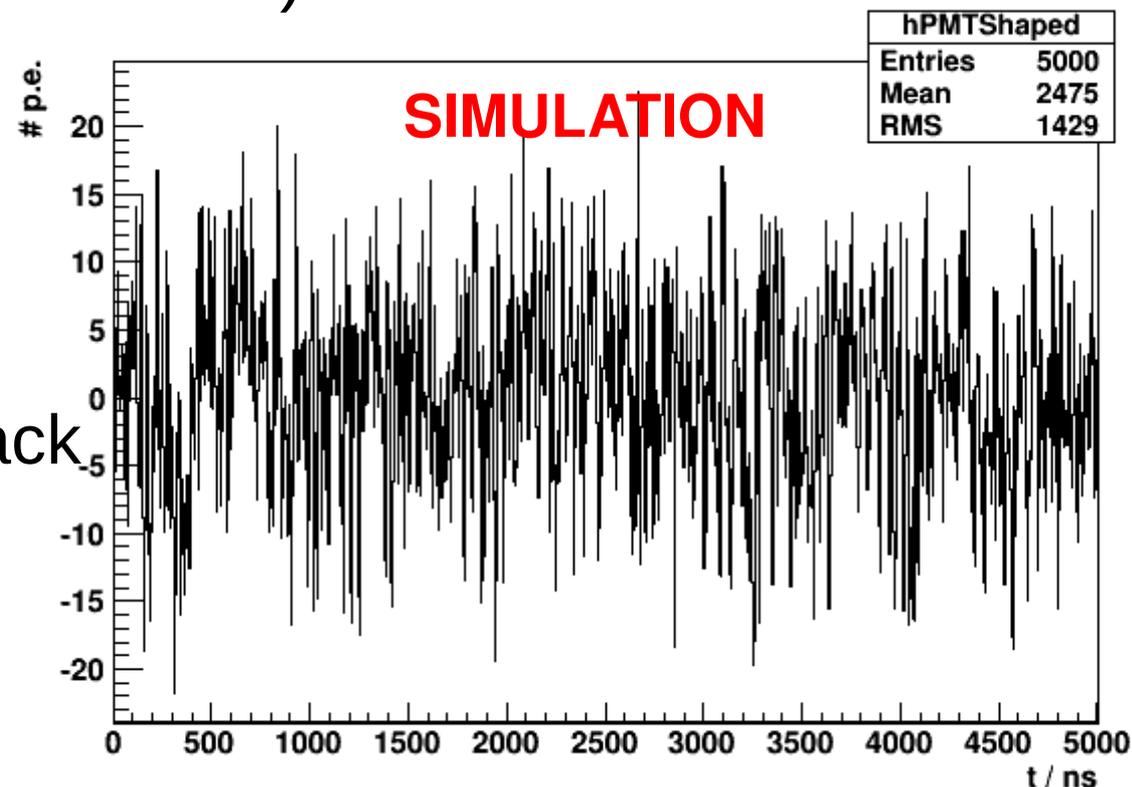
- Shower simulation: CORSIKA 6.735
- Detector simulation: sim\_score
  - Based on iact package (K. Bernlöhr, sim\_skeleton.c)
  - Atmospheric transmission: MODTRAN
  - Tabulated Winston Cone acceptance (ray traced)
  - Tabulated PMT QE =  $QE(\lambda)$  (manufacturer)
  - Pulse shaping: Pulse shape as in V. Henke, Dipl. Thesis
  - Trigger: Next-Neighbour array trigger (1  $\mu$ s window)
  - NSB: added during signal readout (storage)

# Simulation Data Flow



# Night-Sky Background

- NSB rate: La Palma (Mirzoyan & Lorentz 1994, MPI-PhE/94-35)
- Random photons equally distributed in time
- Simulate 4 modules with Pulse shaping: “Henke” shape
- Simulate 4 discriminators (width 20ns)
- Require local 4-coincidence
- 01/09/2009 – 28/02/2009:  
**NSB measurement** in outback  
(D. Hampf)



# NSB in Australia

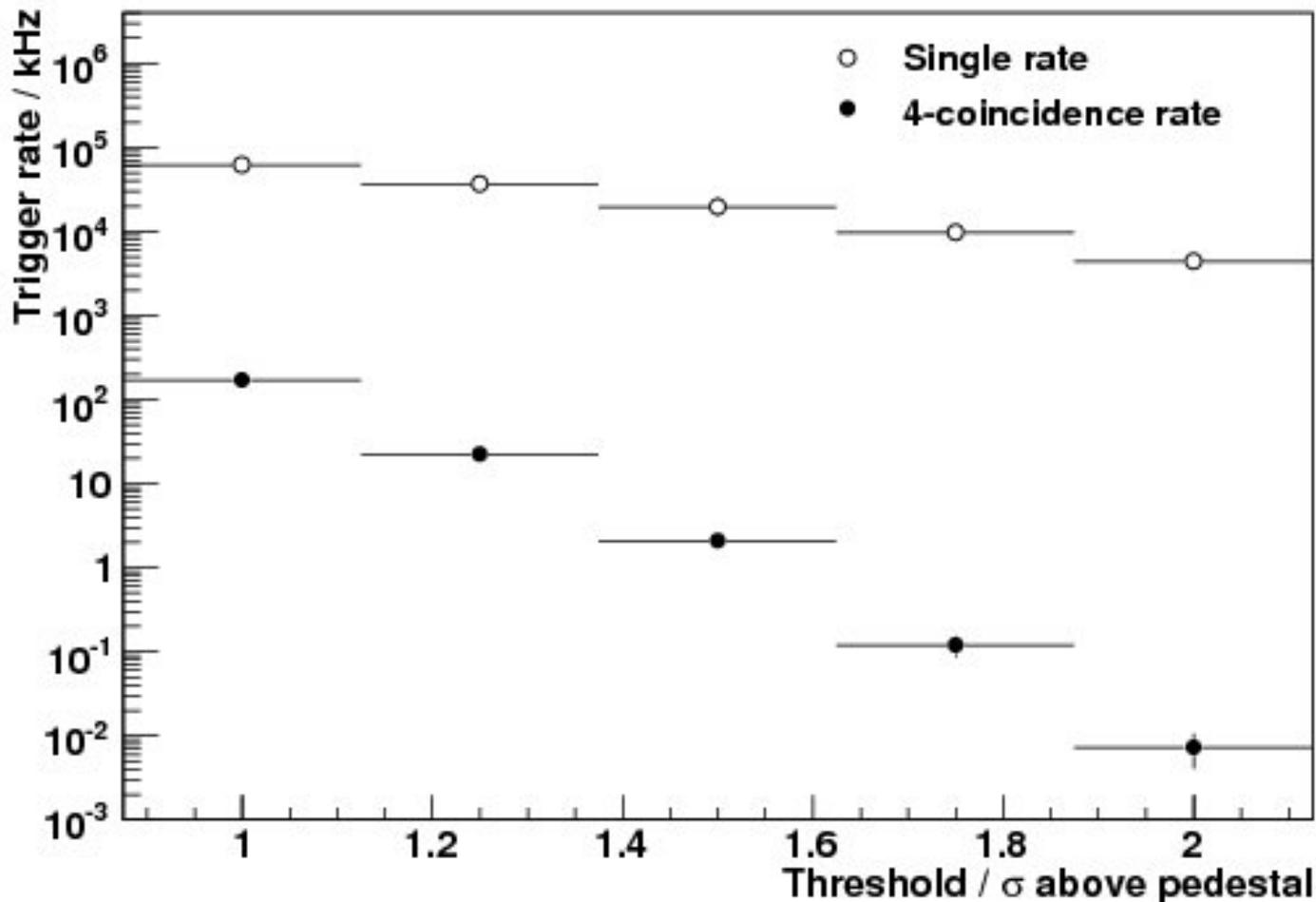
- Plan: Use PMT + discriminator + scaler for single-p.e. Counting
- Possible alternative: DC current measurement
- Use filters for spectrally resolved measurement
- Final experimental setup under development
- D. Hampf leaving on November 1st... (DAAD 4 month stay)

# Night-Sky Background

Suppress NSB → want high PMT threshold

Energy threshold → want low PMT threshold

Reconstruction → want low PMT threshold



$$\Omega = 0.85 \text{ sr (30}^\circ\text{)}$$

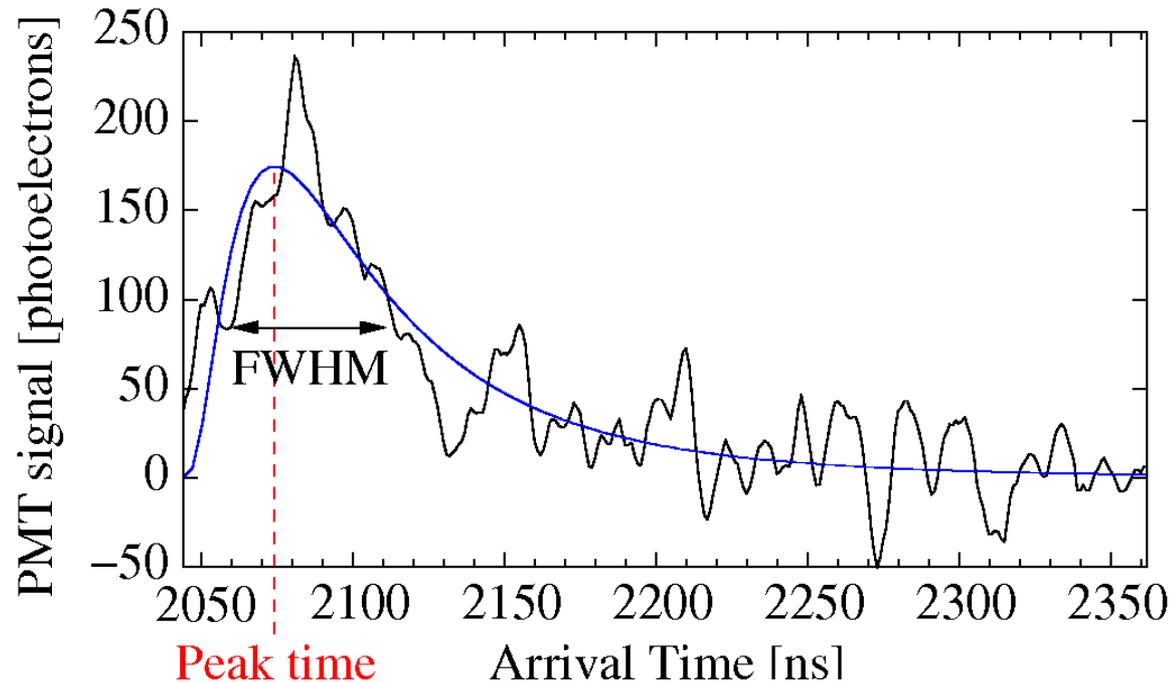
$$A = 1.5 \text{ m}^2$$

$$R_{\text{NSB}} = 2 \times 10^{12} / \text{m}^2 \text{ s sr}$$

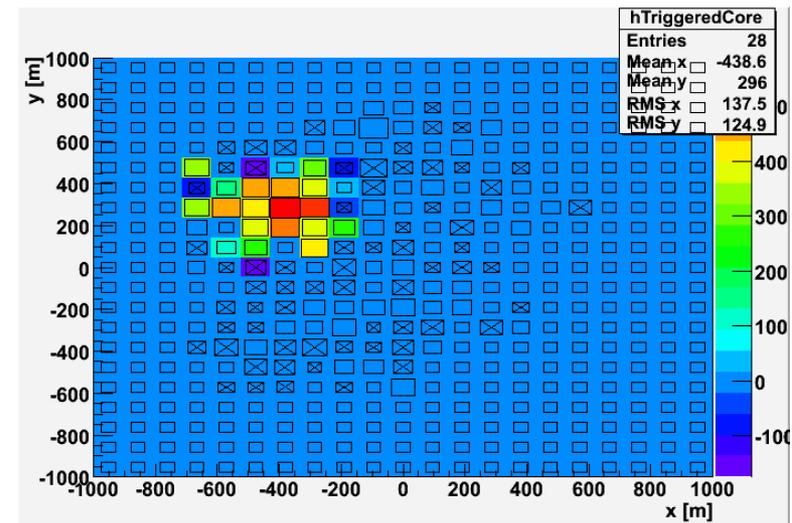
Shower depth reconstruction: Improve S/N: station stacking

# Reconstruction

## Amplitude & Timing

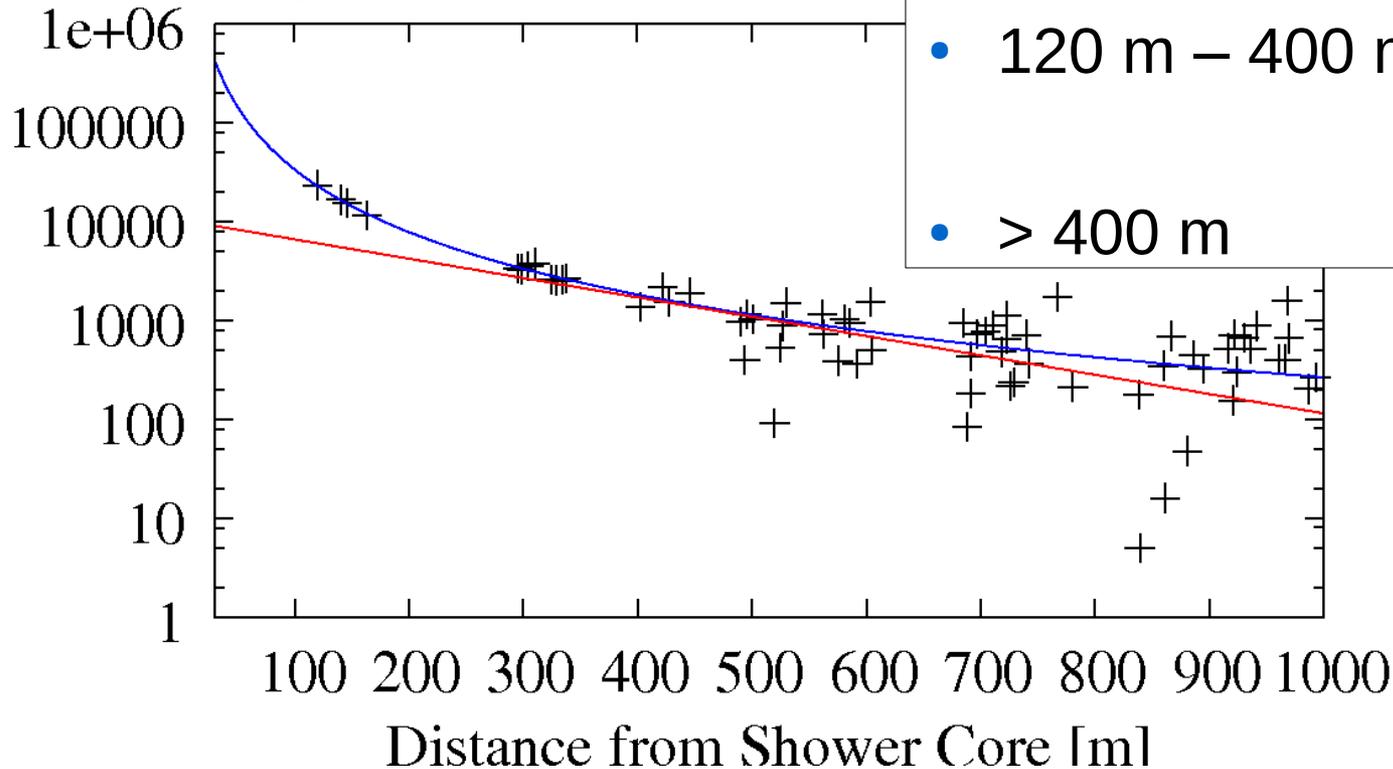


- So far usage of basic algorithms
- Fitting is not optimized yet
- Cuts were chosen ad hoc
- Results are preliminary
- Potential for improvement



# Amplitude: The Lateral Density Function

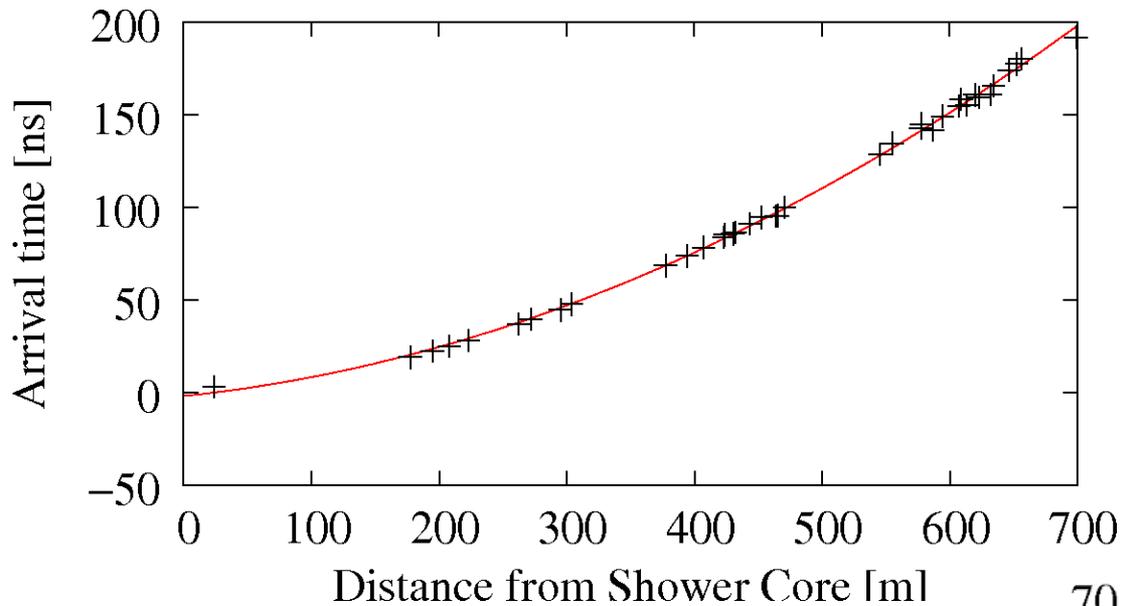
Number of photons



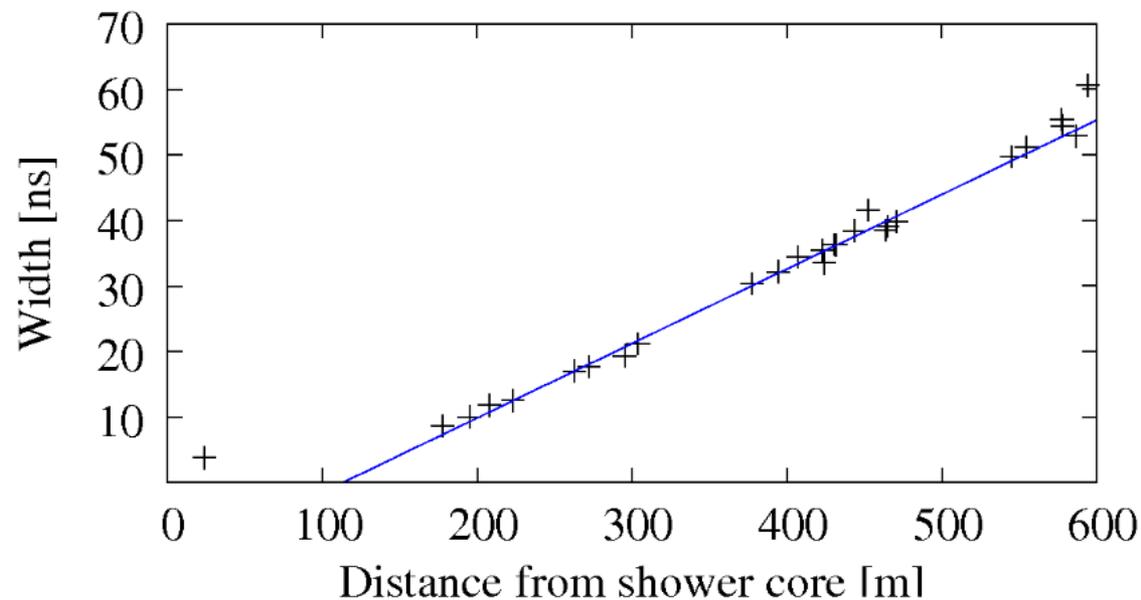
- < 120 m exp, large shower-to-shower fluctuations
- 120 m – 400 m powerlaw, good S/N
- > 400 m exp, bad S/N

- Previous experiments: mainly inner fluctuative part
- SCORE: mainly > 120 m (powerlaw, exp)  
Advantages: small shower-to-shower fluctuations, large lever arm !

# Timing: Arrival Time Distribution



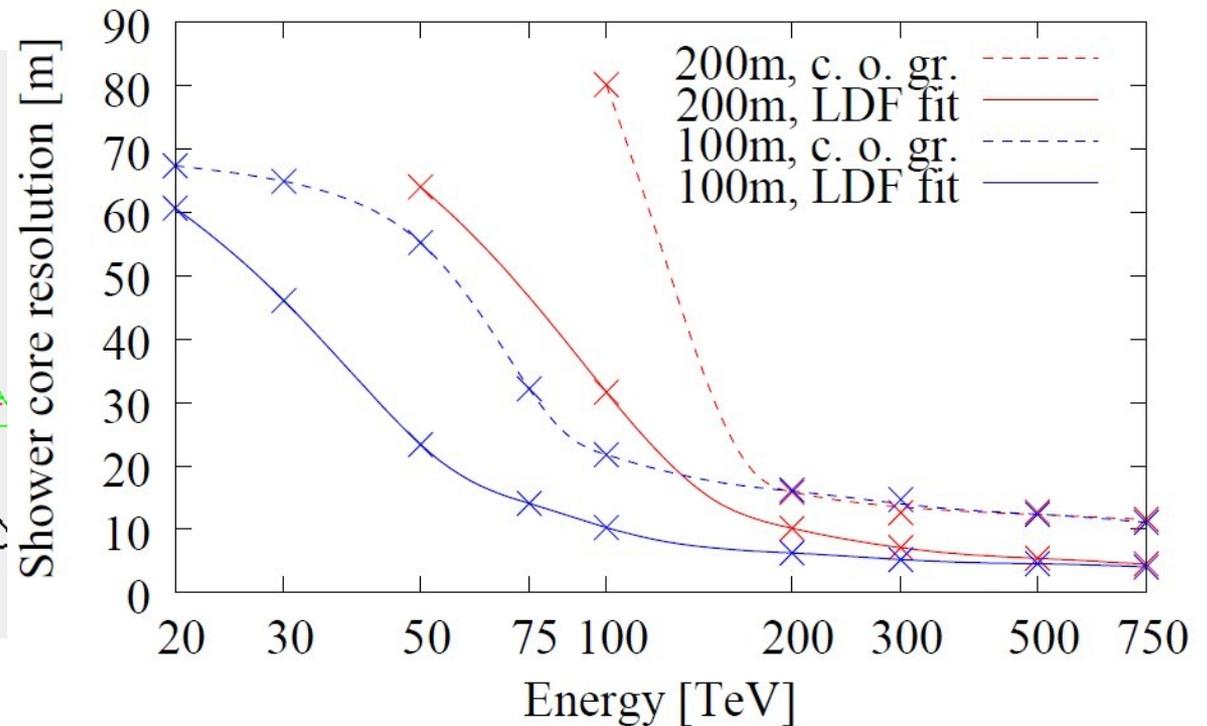
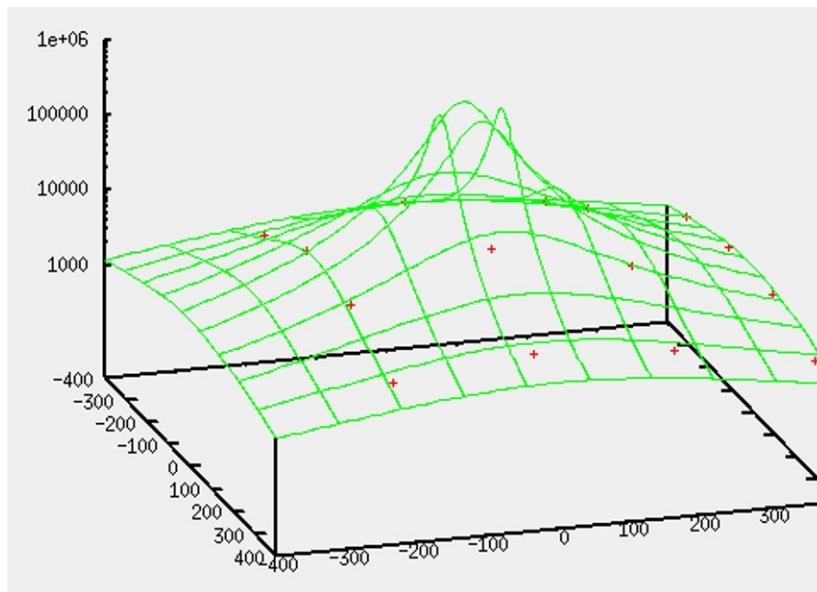
**Peak of arrival time distribution:  
parabolic dependency of core**



**Width of arrival time distribution:  
linear dependency**

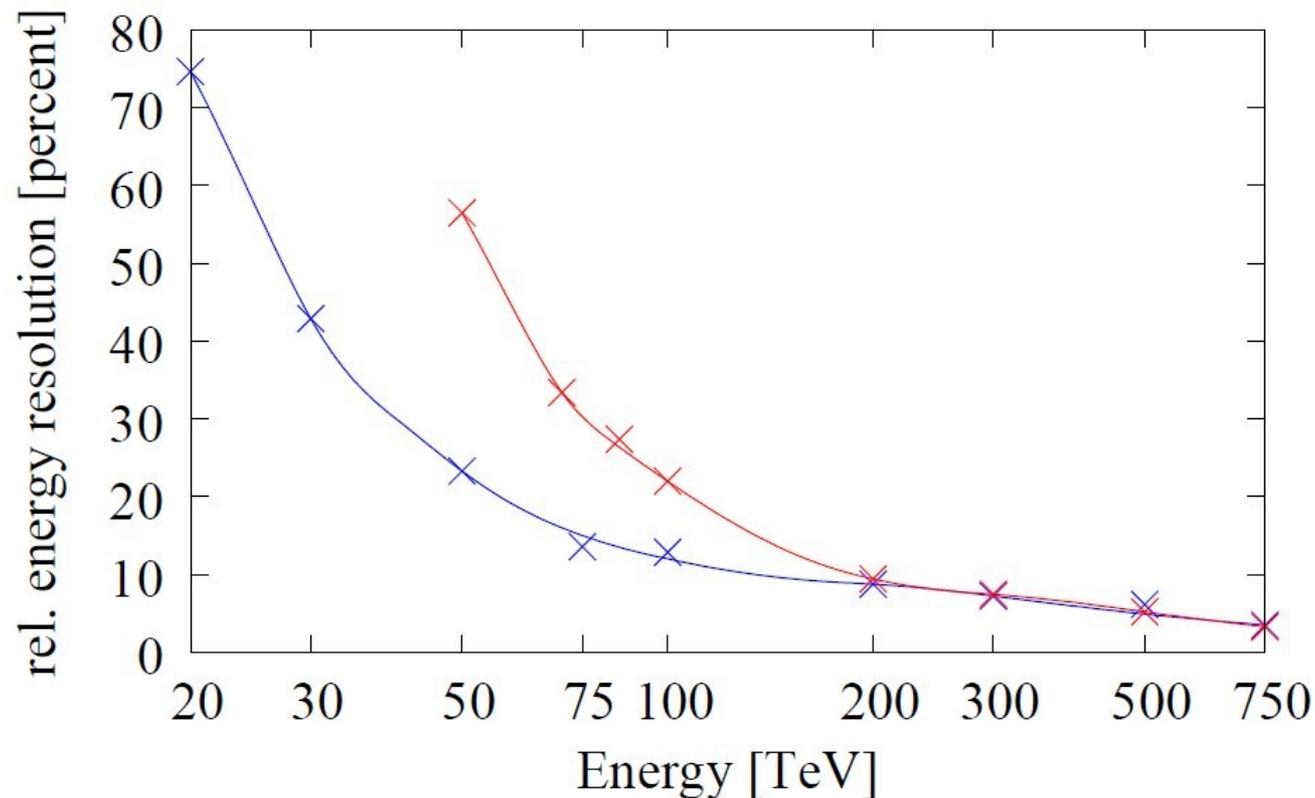
# Shower Core Impact

- Trivial method: COG of Cherenkov light distribution on the ground
- Standard method: Fit LDF to station data



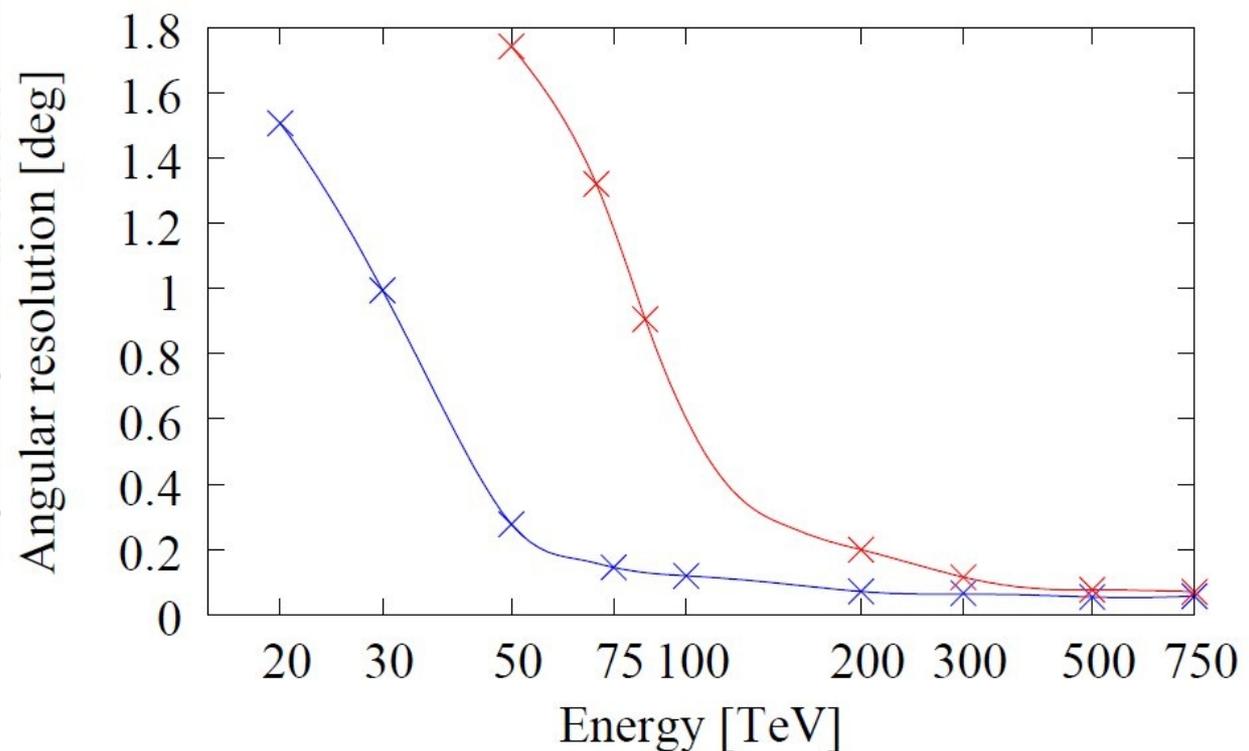
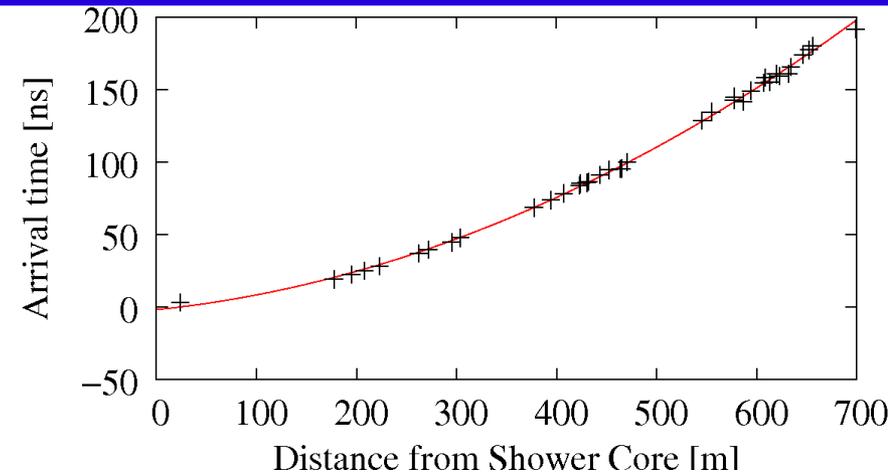
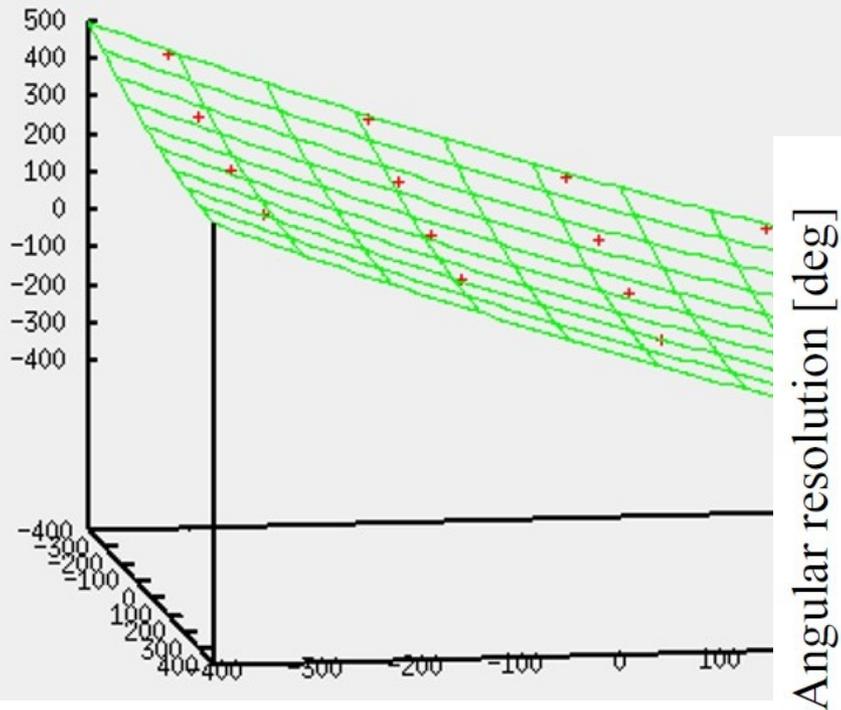
# Primary Energy

- Photondensity on observation level:  $P(E) \sim n E$
- Energy reconstruction:  
fit LDF and use value of fit function at 220 m
- $E(P) = \exp(\ln P - \ln n)$



# Primary Direction

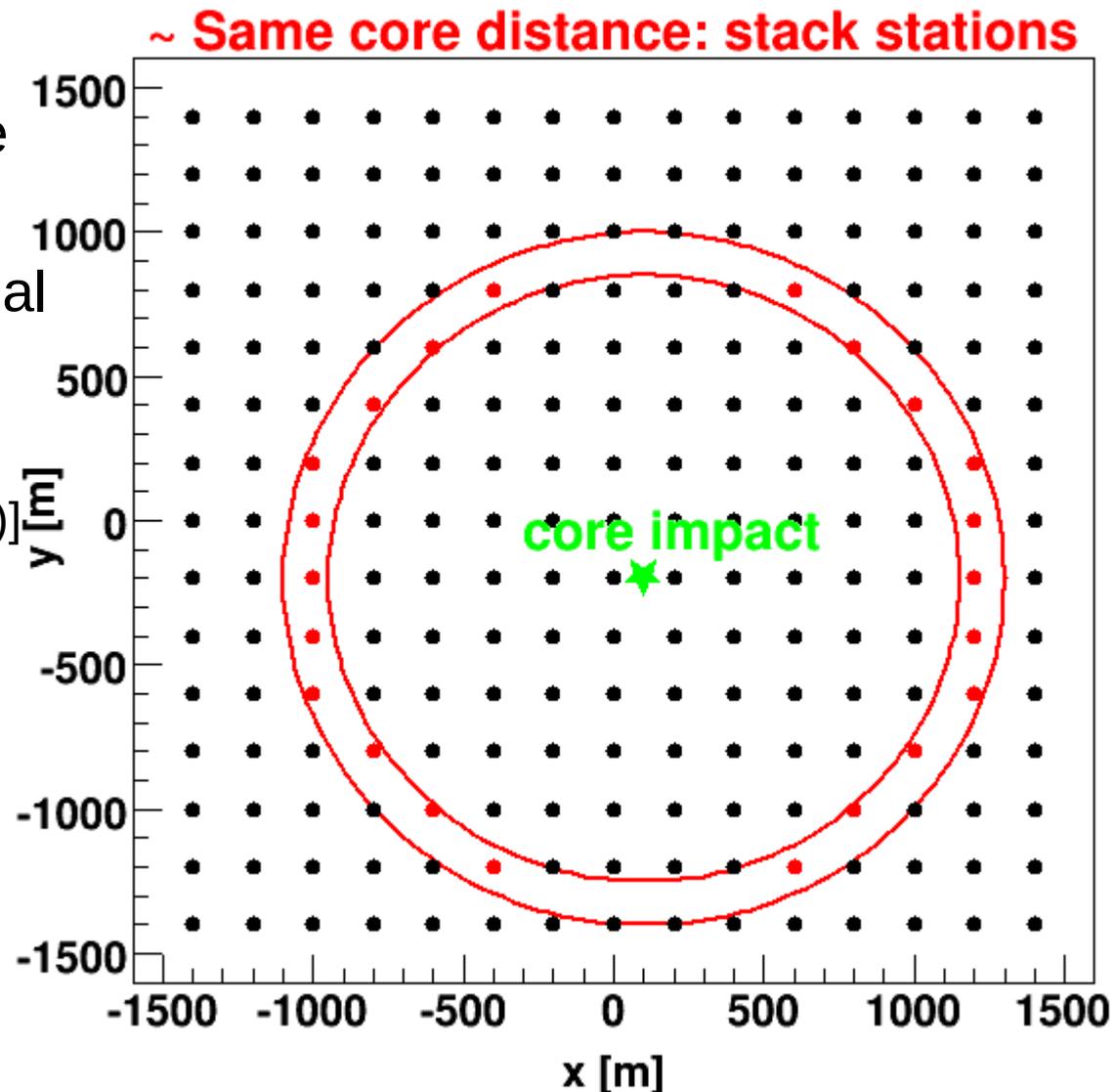
Fit 2D Parabola + plane  
to measured arrival times



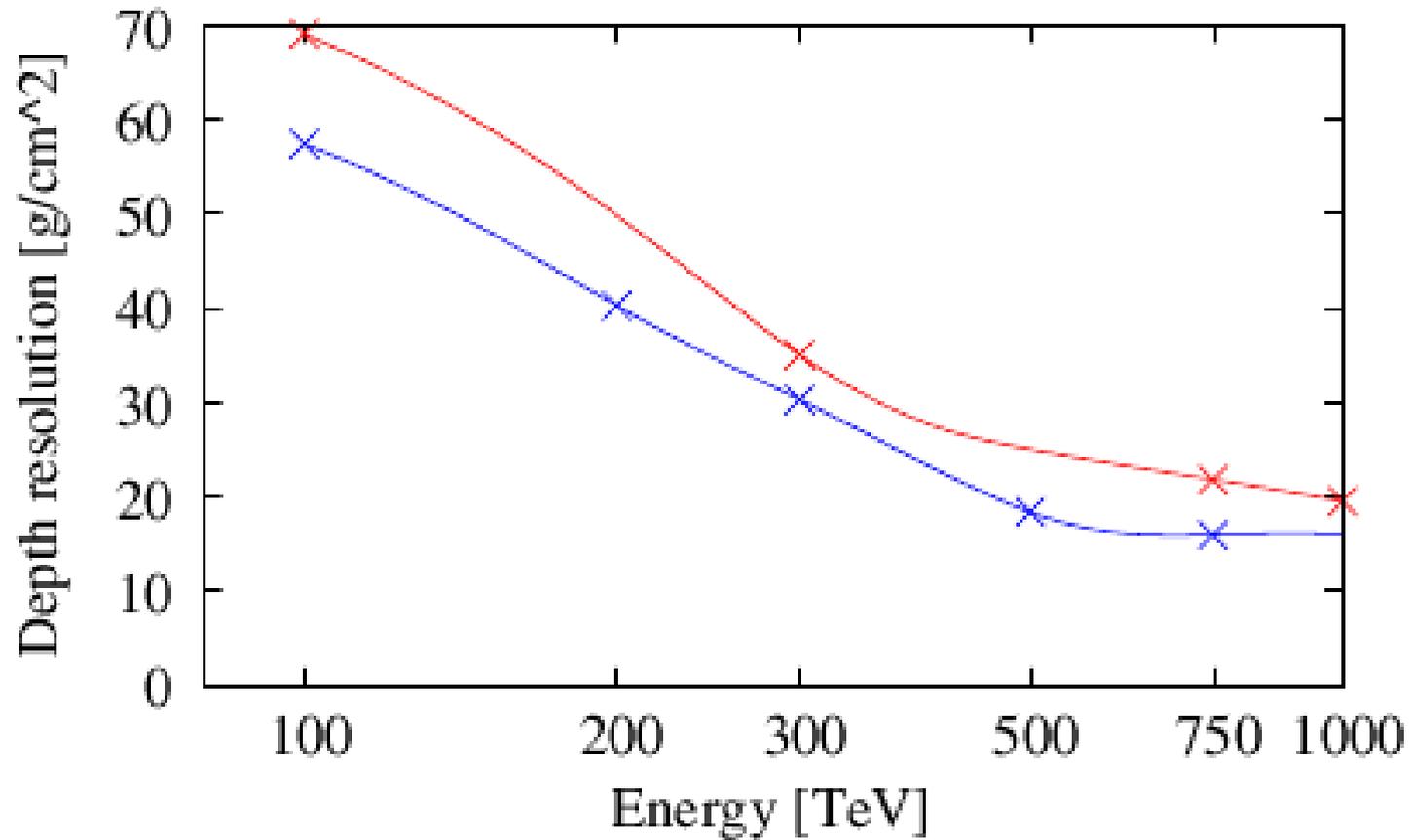
# Shower Depth

- Intensity method: slope of LDF(50 m) / LDF(220 m)
- Timing methods:

- 1) Stack stations with same core distance: better S/N
- 2) Fit log-normal function to signal
- 3) **Signal width:**  
depth  $\sim \langle w \rangle$   
 $\langle w \rangle = \text{avg}[\text{width}(300\text{m}), \text{width}(400\text{m})]$
- 4) **Signal peak:**  
depth  $\sim a$   
(from time peak fit:  $a x^2 + b$ )



# Shower Depth



# Shower Depth & Gamma/Hadron Separation

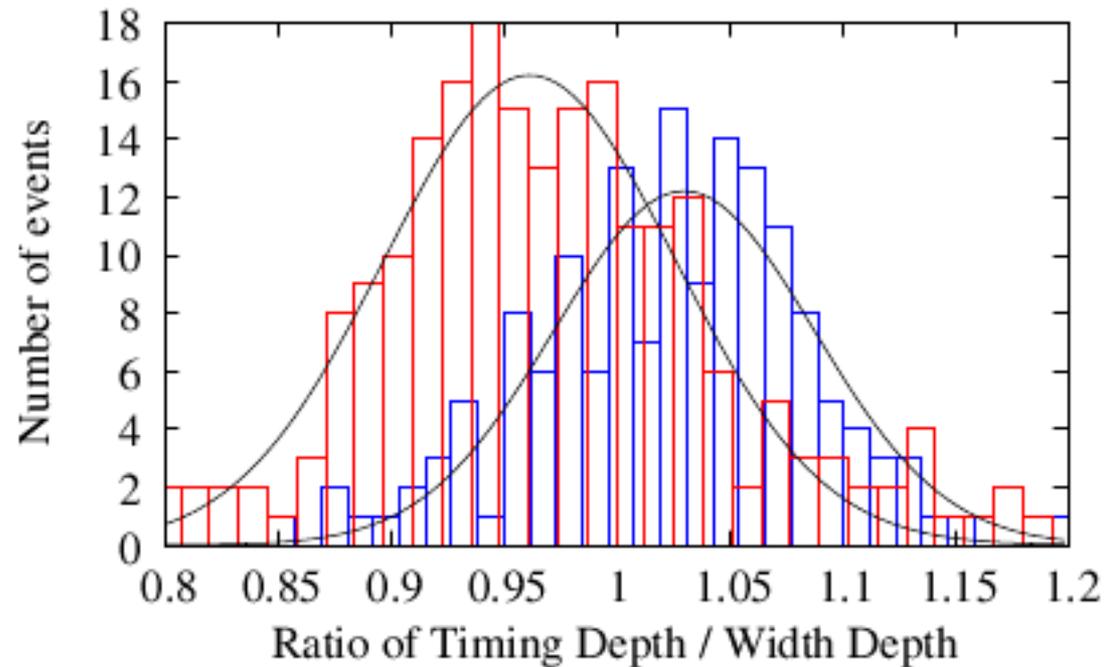
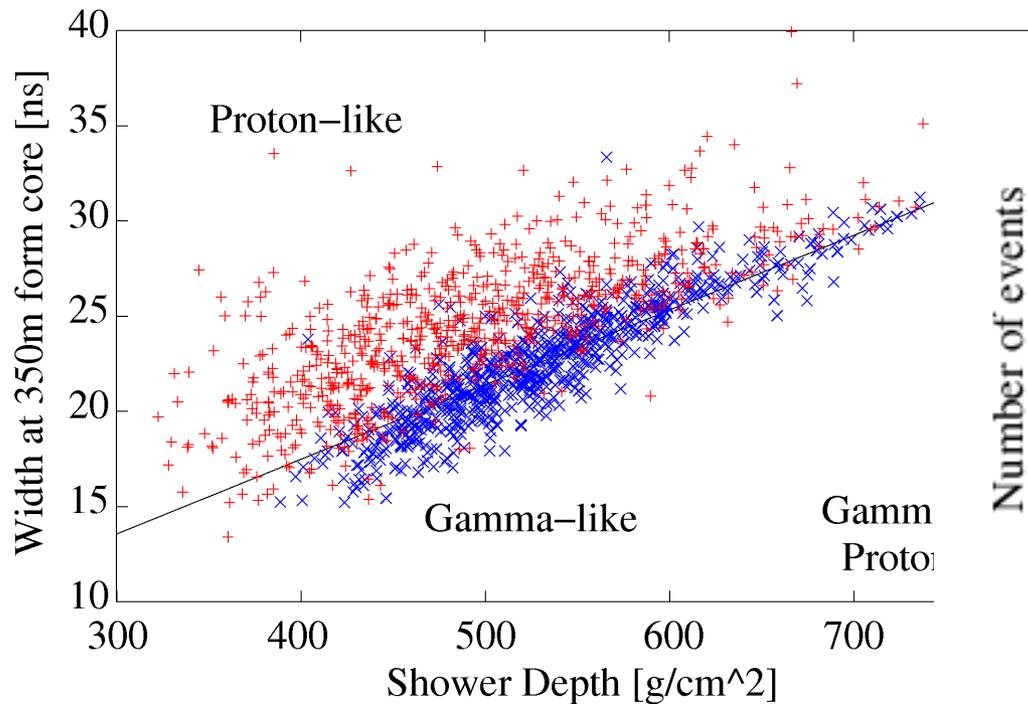
## Differences in longitudinal shower development:

- **Gammas:** most Cherenkov light emitted near shower maximum
- **Hadrons:** wider depth range of emission
- Longer hadronic showers:  
**overestimation of hadronic shower depth by width method !**

**Use this difference for gamma/hadron separation**

# Gamma / Hadron Separation

- Gamma/hadron separator:  $D_{\text{peak}} / D_{\text{width}}$

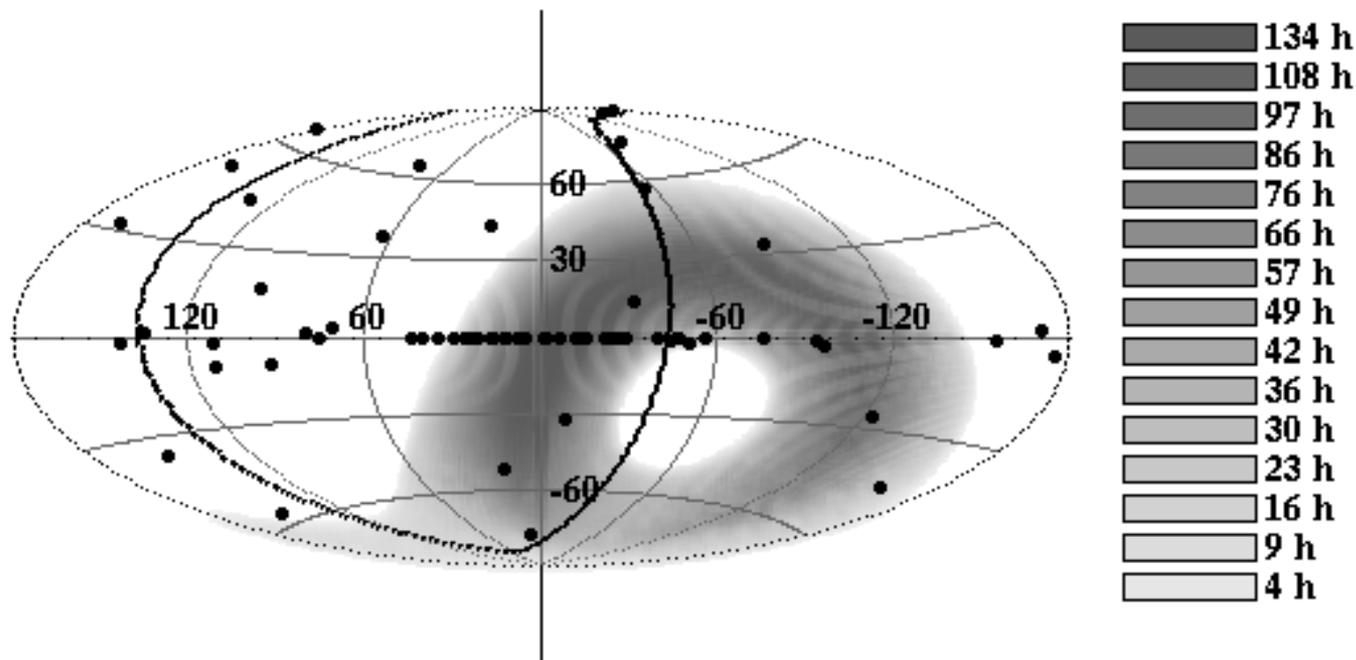


# Flux Sensitivity

- Minimum point-source flux for which:  
 $5\sigma$ ,  $>50$  events, in 5 years (500 hours)
- Significance:  $(\text{on-off}) / \text{Sqrt}(\text{on+off}) = N_g / \text{Sqrt}(N_g + 2 N_h)$   
i.e. trivial Li&Ma, no alpha factor
- Calculate integral numbers  $N_g(E)$ ,  $N_h(E)$ :
  - Gamma: pevatron spectrum
  - Hadrons: hoerandel polygonato model
- Simulated effective areas for Gamma, p, He, CNO, Fe

# Exposure in Australia

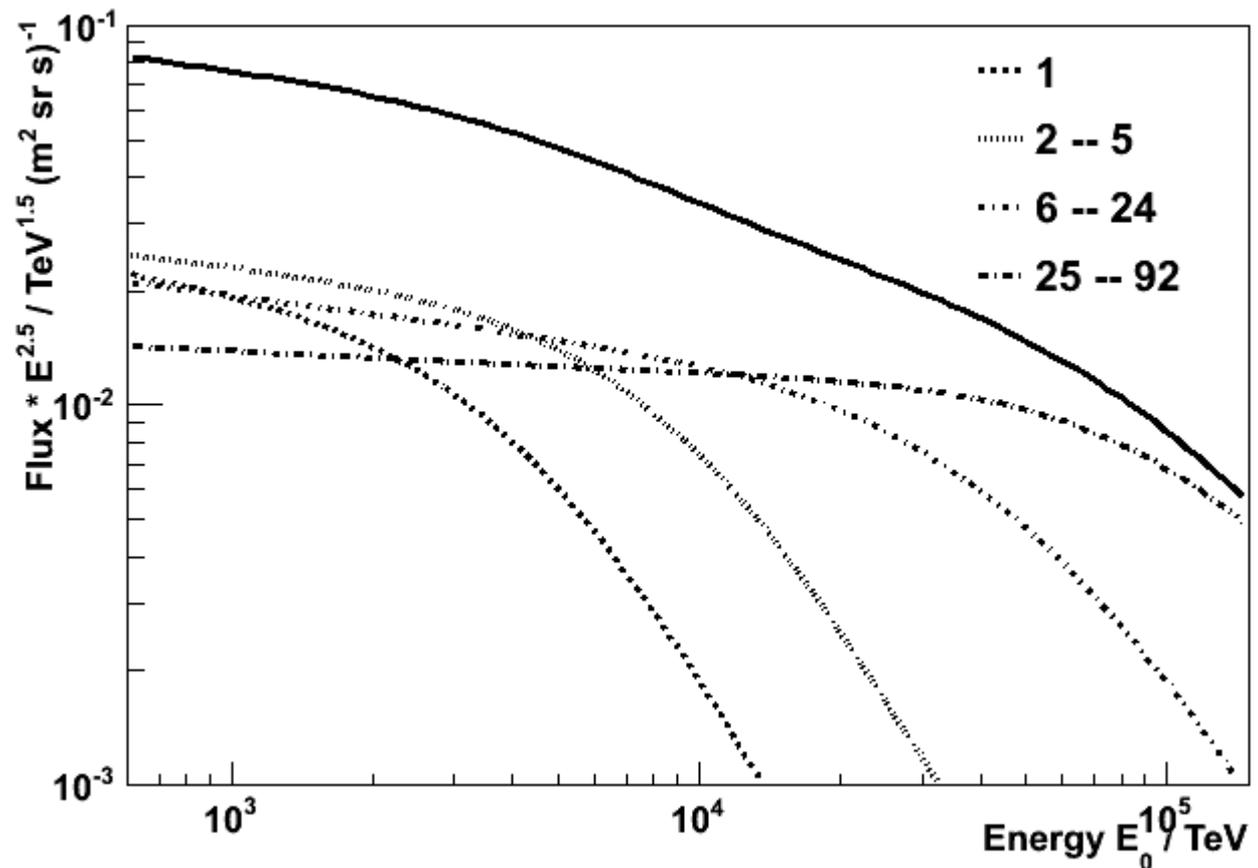
- Exposure time per year: 80 – 130 hours
- Tilt arrays after 5 years of operation:
  - *Tilted north field & tilted south deep field*



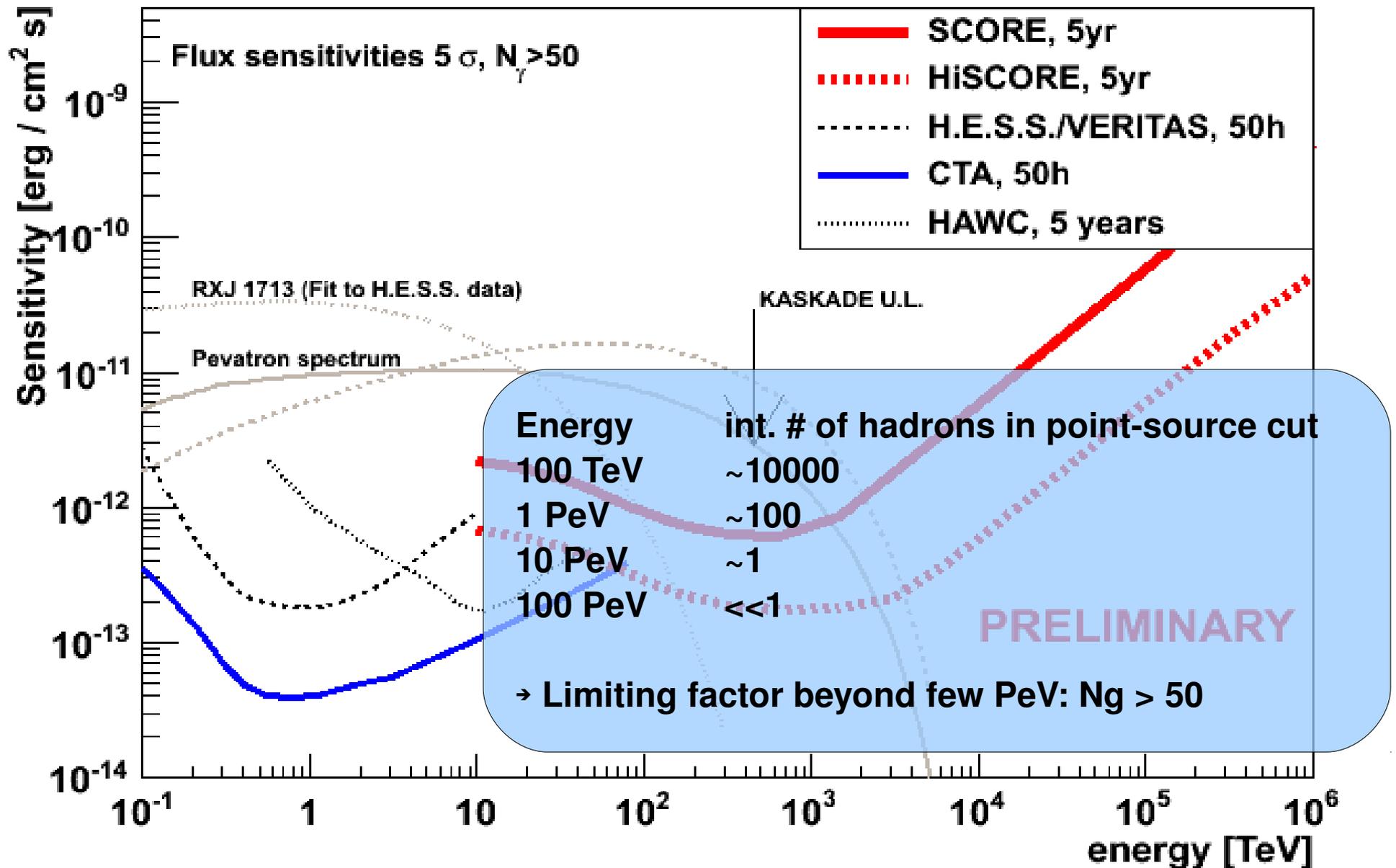
Daniel Hampf 2008

# Hadrons

- Hoerandel 2003: polygonato model
- Hadron rates for SCORE, 10 m<sup>2</sup>, 0.85 sr (theoretical rates):
  - E > 10 TeV: 25 kHz
  - **E > 100 TeV: 500 Hz**
  - E > 1 PeV: 10 Hz

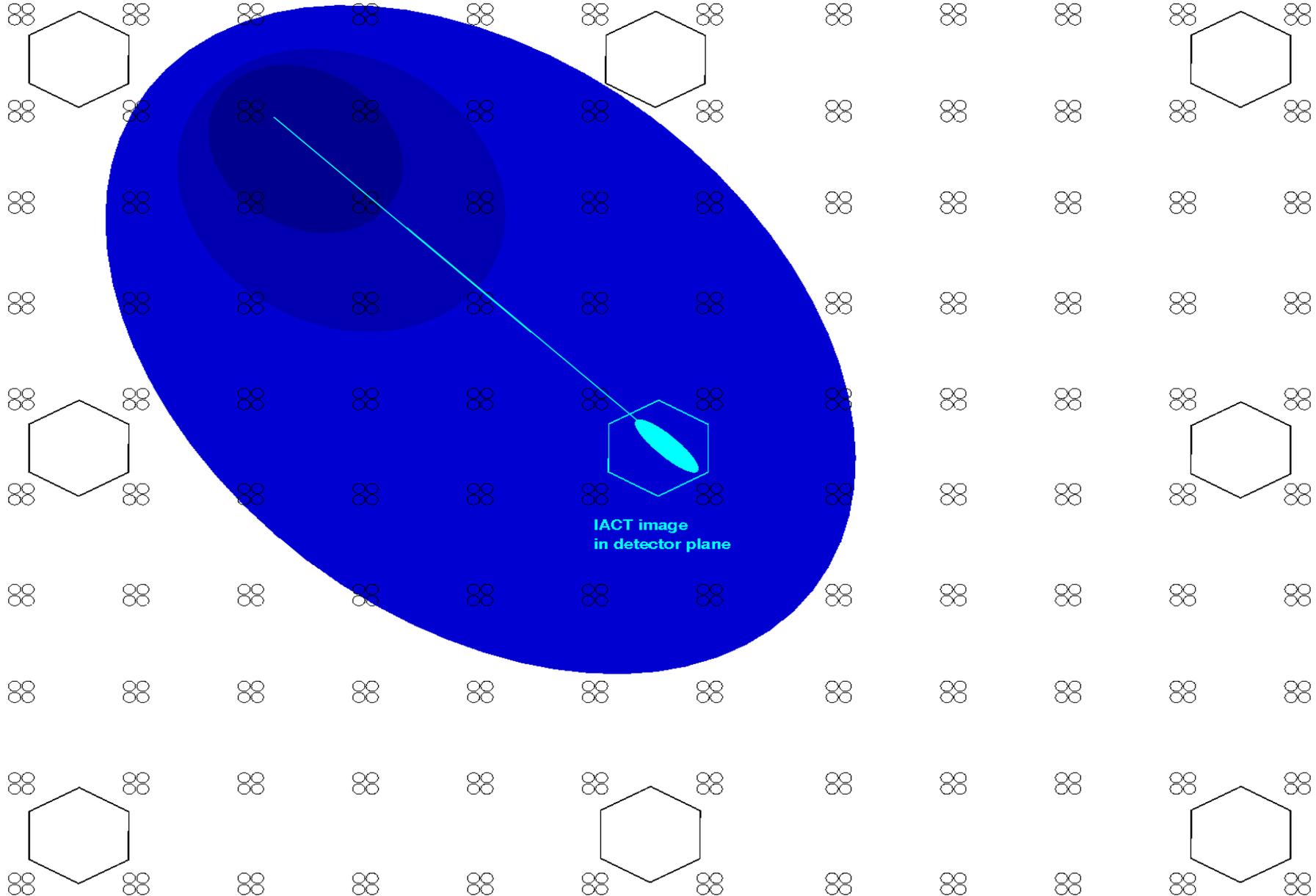


# SCORE First Simulation Results



# Combination with IACTs

SCORE Detector stations -- really not to scale !



# Combination with IACTs

- Sharing site infrastructure
- Use SCORE stations for **shower impact reconstruction**
  - **improvement for large stereo angles**
  - **monoscopic telescopes** distributed on **larger area**.  
E.g. CTA: same number of small telescopes but larger distances giving **higher  $A_{\text{eff}}$  / channel ratio !**
- Caveat: observations constrained to station viewcone (overcome this with station steering ...)
- Working on ... testing this in simulation

# Outlook

- **Cooperation is welcome !**
- **H<sub>i</sub>SCORE**  
Hundred Square-km Cosmic ORigin Explorer
- **Extension / Synergies** with other techniques
  - Radio (LOFAR)
  - Szintillation counters (hybrid array)
  - Possible combination with imaging Cherenkov technique

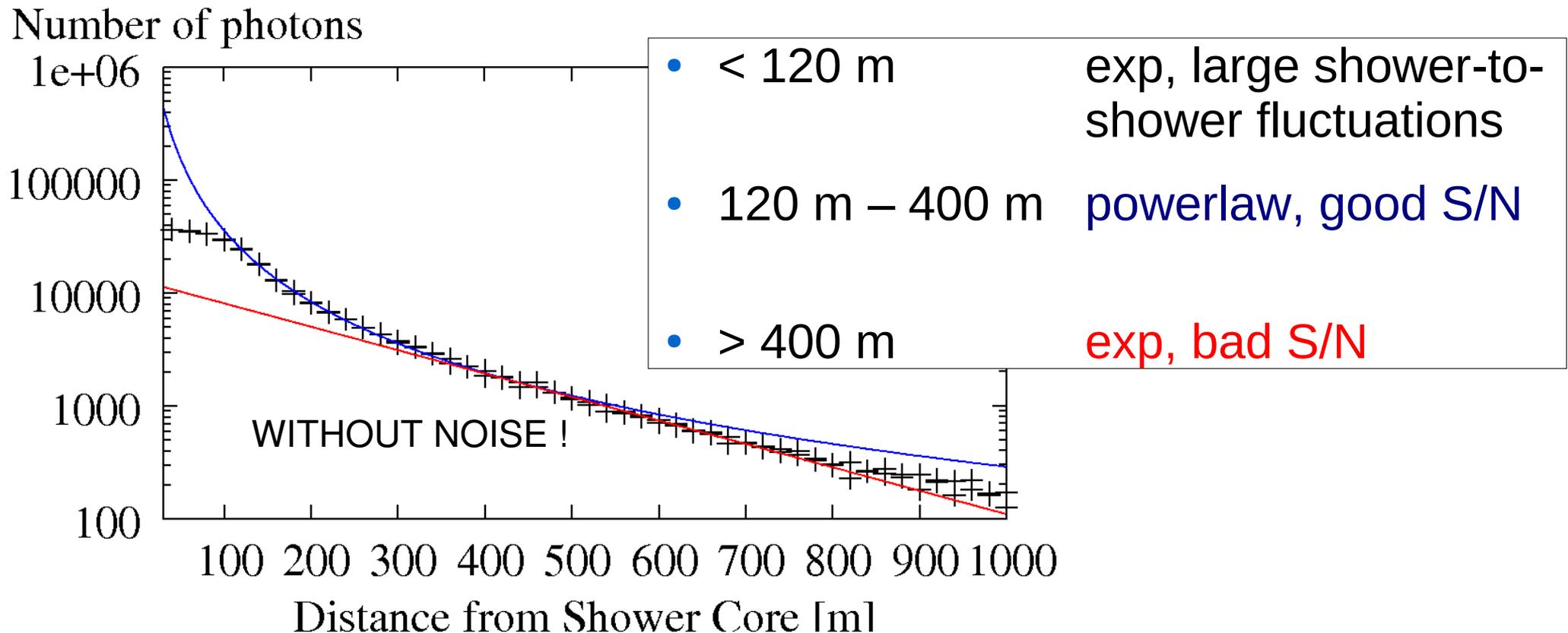
# Alternatives / Extensions

- Daytime-measurements with scintillator material in lid: 100% duty cycle
- Combination with imaging technique:
  - provide core-reconstruction for low-density telescope grid (even monoscopic ?)
  - Instrumentation of larger area for highest energies
- Combination with radio detection technique ?
- ...

# Expected Trigger Rates

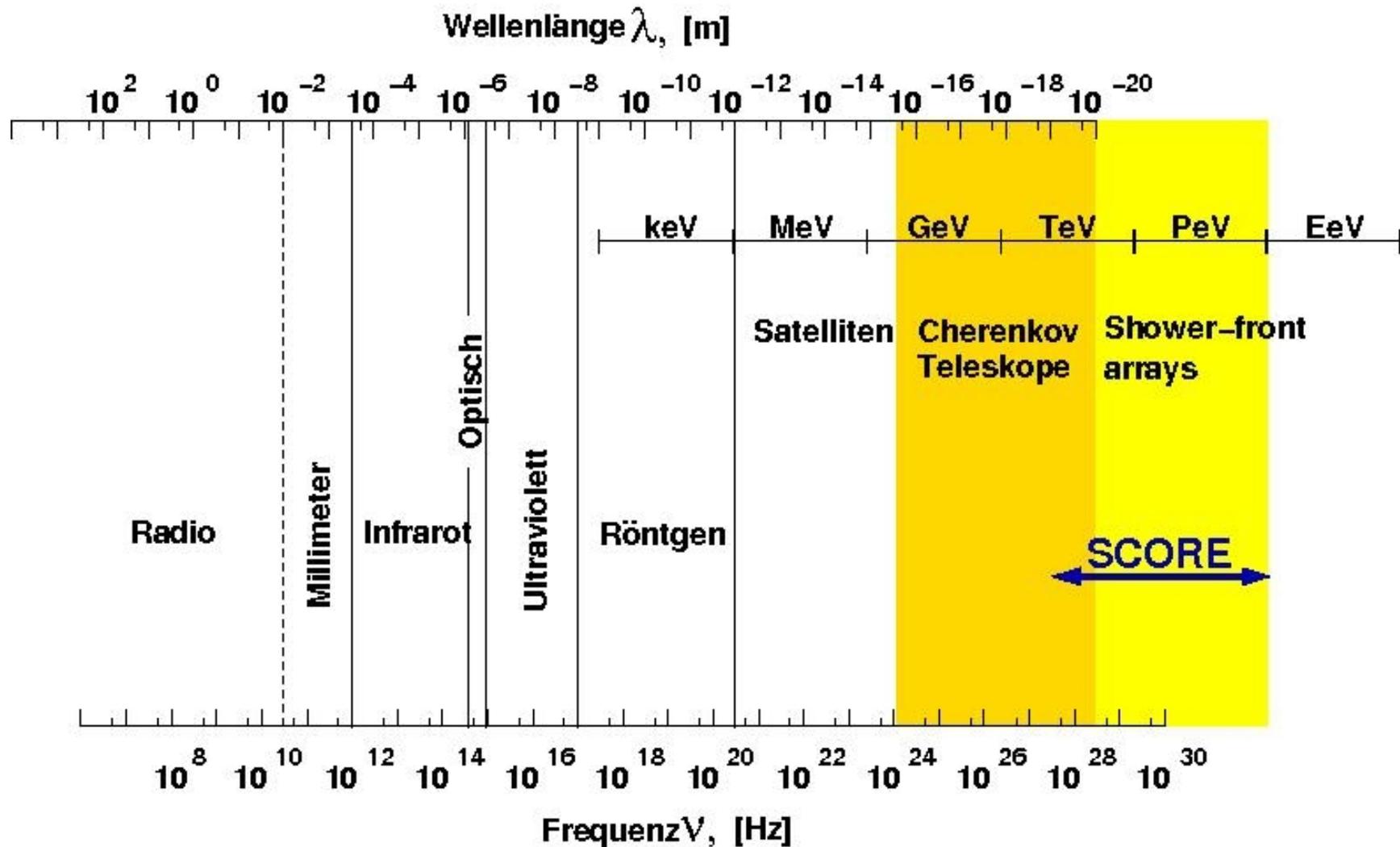
- Trigger conditions:
  - 1.5 sigma above NSB per channel
  - 4-channel coincidence per station
  - 2-station coincidence (array trigger)
- NSB:
  - 4-coincidence: ~1 kHz
  - 4-coincidence @ 2 sigma above NSB: ~10 Hz
- Hadrons:  $O(1 - 10 \text{ kHz})$  (depending on layout)

# Amplitude: The Lateral Density Function



- Previous experiments: mainly inner fluctuative part
- SCORE: mainly > 120 m (powerlaw, exp)  
Advantages: small shower-to-shower fluctuations, large lever arm !

# The last Observation Window



**SCORE = Study for a Cosmic ORigin Explorer**

**Aim at:  $10 \text{ TeV} < E < 1 \text{ EeV}$**

# (Some) Physics Cases for SCORE

Gamma-rays:  $E > 10 \text{ TeV}$

Cosmic-Rays:  $100 \text{ TeV} < E < 1 \text{ EeV}$

- **Astroparticle physics**

- Origin of Cosmic-Rays
- Unidentified sources: where do they stop?
- Local Supercluster
- Absorption in Galactic radiation fields and CMB

- **Particle physics**

- Axion / hidden photon search (propagation)
- Lorentz Invariance violation (propagation)
- Measurement of p-p cross-section

# Cherenkov Technique

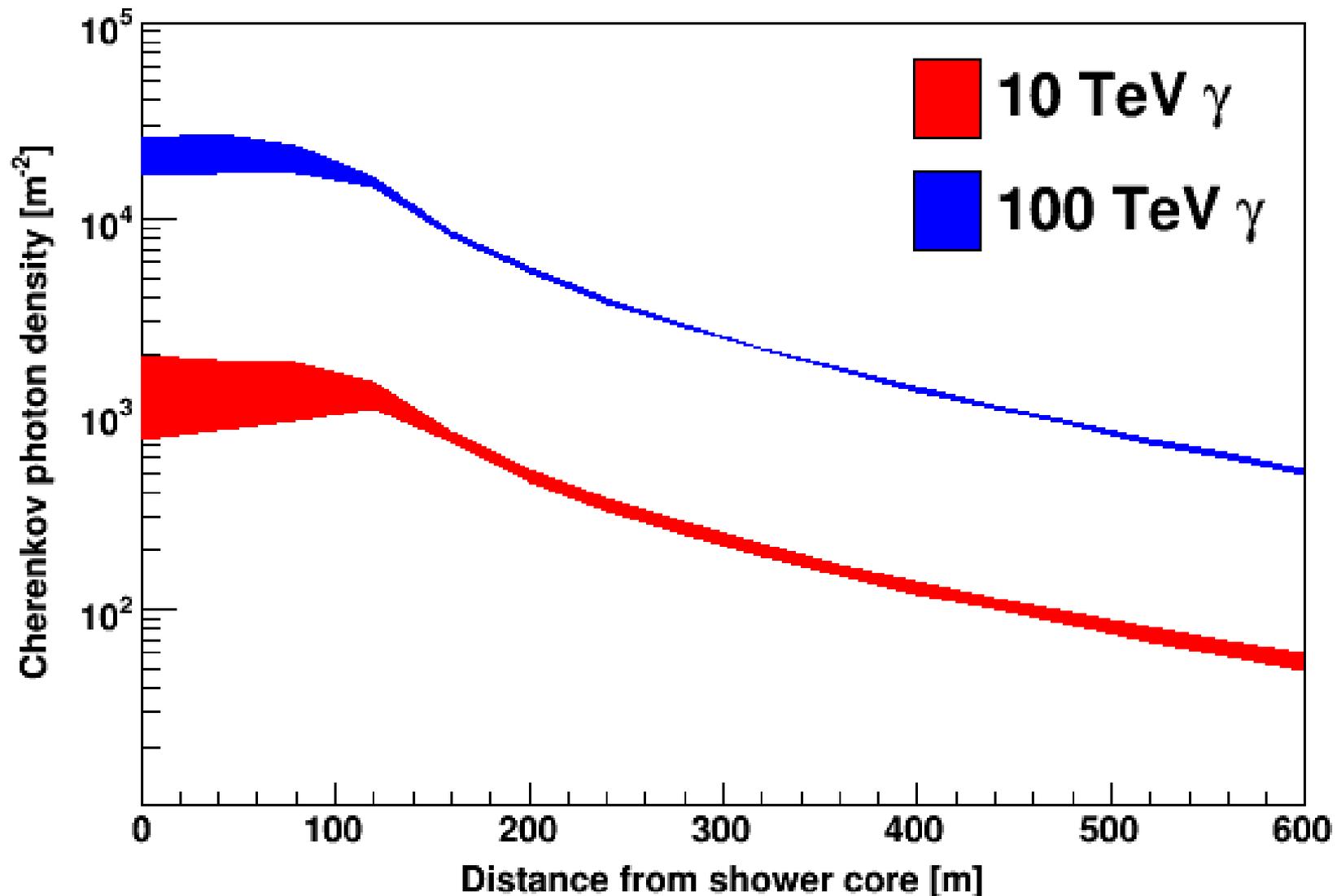
## Challenges

- Gamma-hadron separation
  - Night-Sky Background suppression
- 

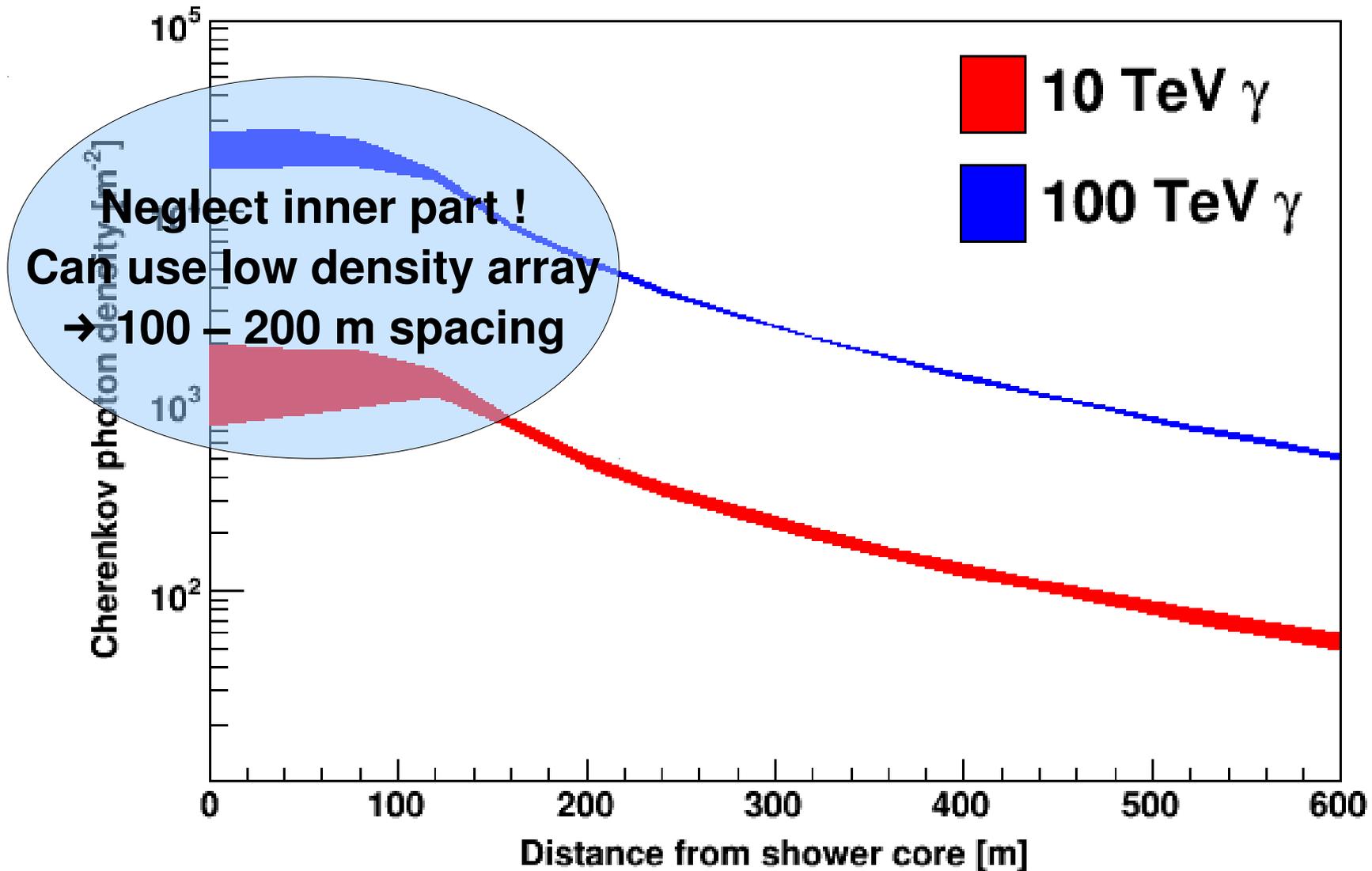
## Benefits

- High photon-statistics per shower
- Channel-per-km<sup>2</sup> factor
  - IACTs: ~25000
  - SCORE: < 200
- **Lateral photon density distribution ...**

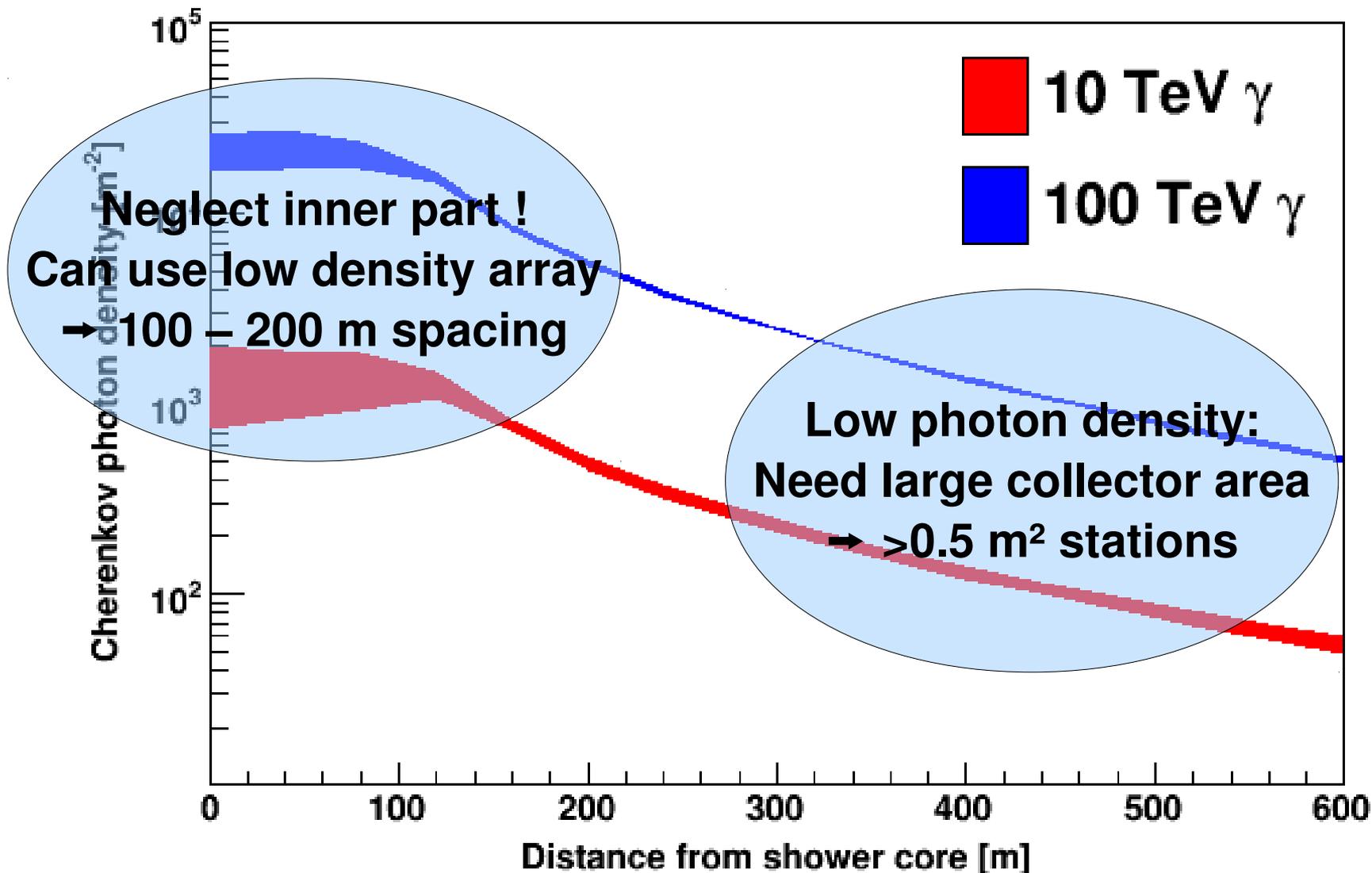
# Lateral Cherenkov Photon Distribution



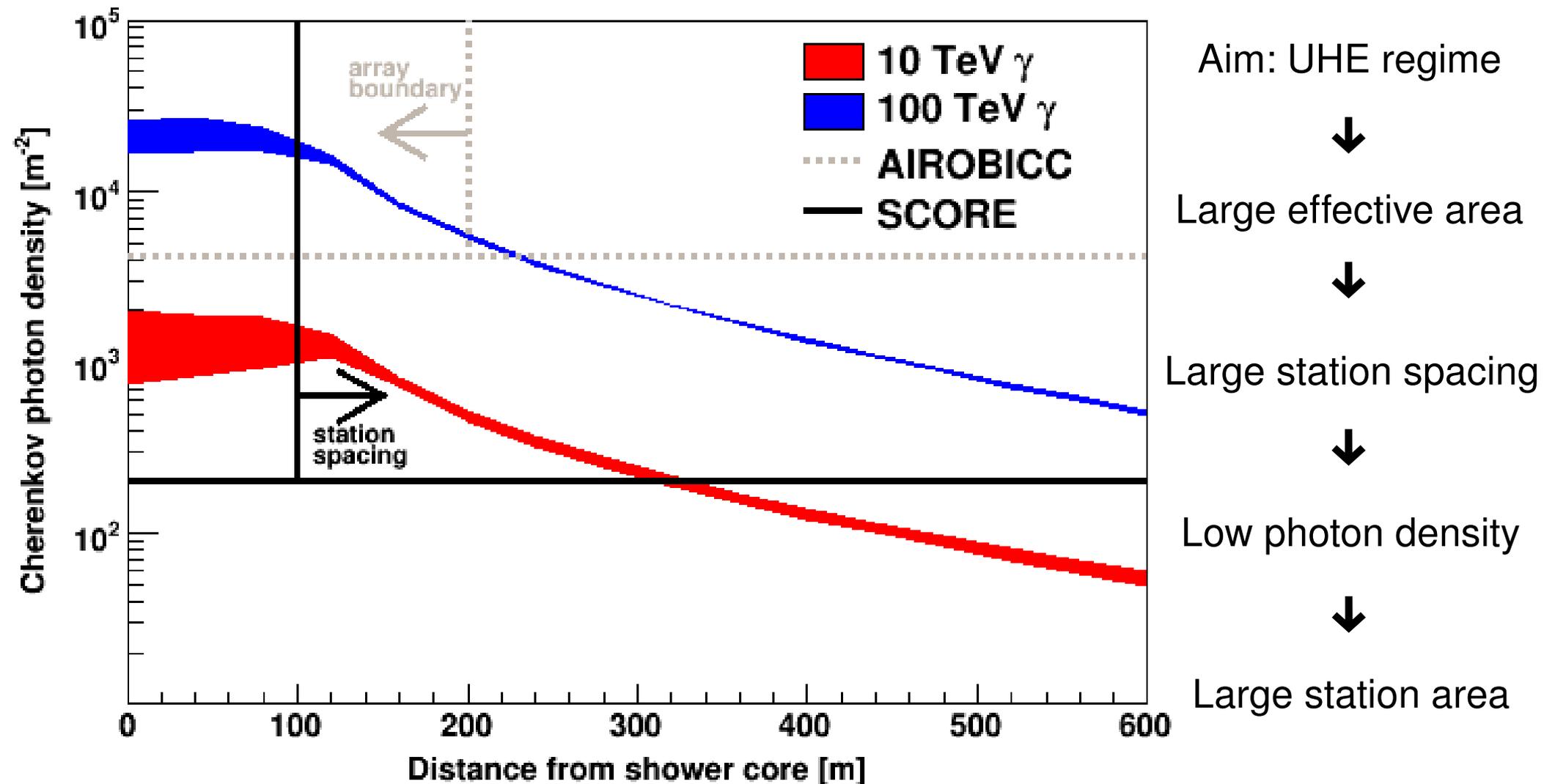
# Lateral Cherenkov Photon Distribution



# Lateral Cherenkov Photon Distribution



# The SCORE Detector



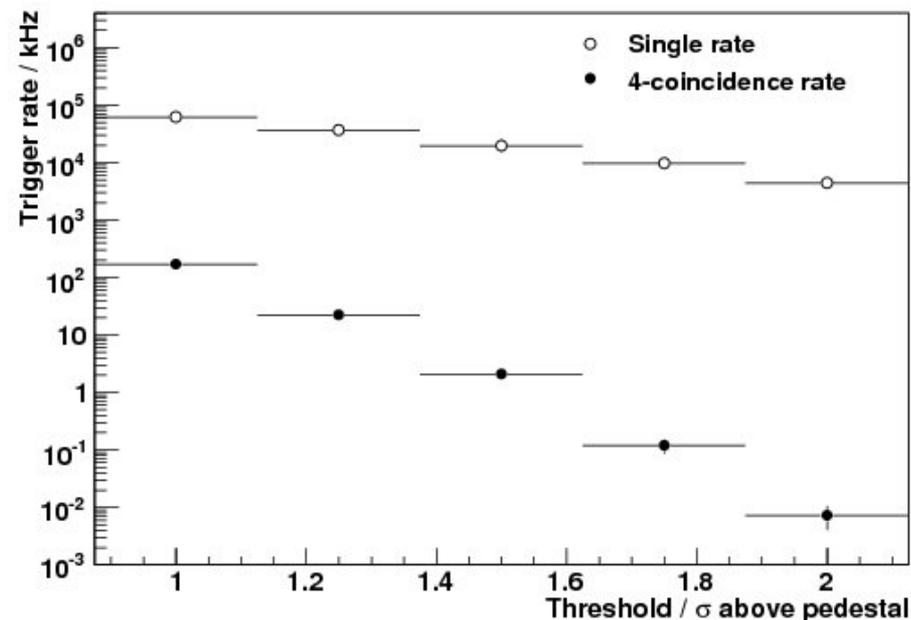
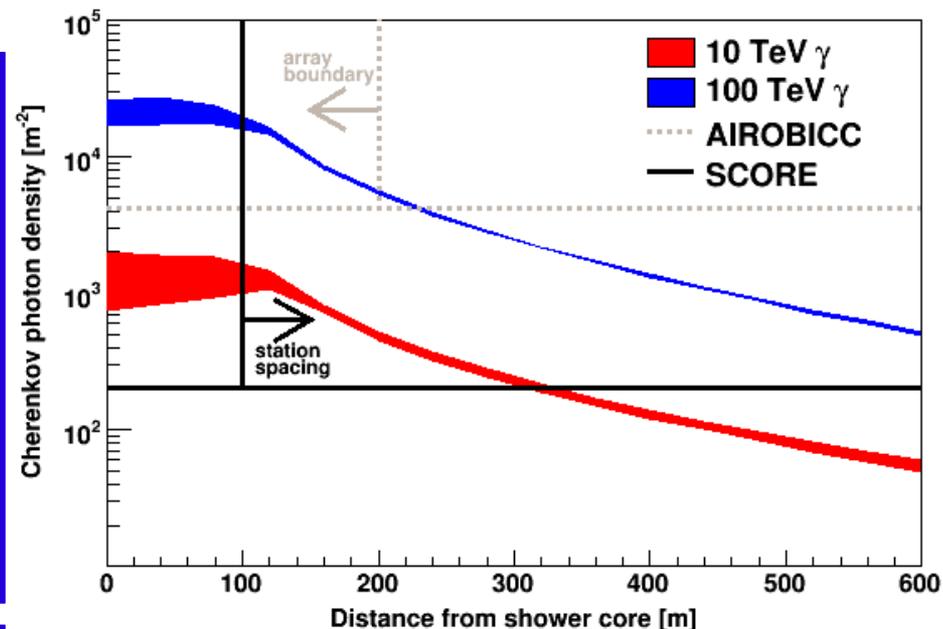
# Cherenkov Technique

## Benefits

- High photon statistics
- Lateral density falls off slowly
- >120m core: low fluctuations

## Limiting factors

- Channel-per-km<sup>2</sup>
  - IACTs:  $\sim 25000$  (imaging)
  - SCORE:  $< 200$  ! (non-imaging)
- Night-Sky-Background



# Station Stacking

- Many stations with same core distance
- Stack stations
- Improves S/N

