

SCORE

Gamma-ray and Cosmic ray astrophysics from 10TeV to 1EeV



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Why SCORE ?
What SCORE ?
How SCORE ?

Astroparticle Physics in UHE regime

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 scale

- Axion / photon conversion
- Hidden photon / photon oscillations
- Lorentz invariance violation
- pp cross-section measurements

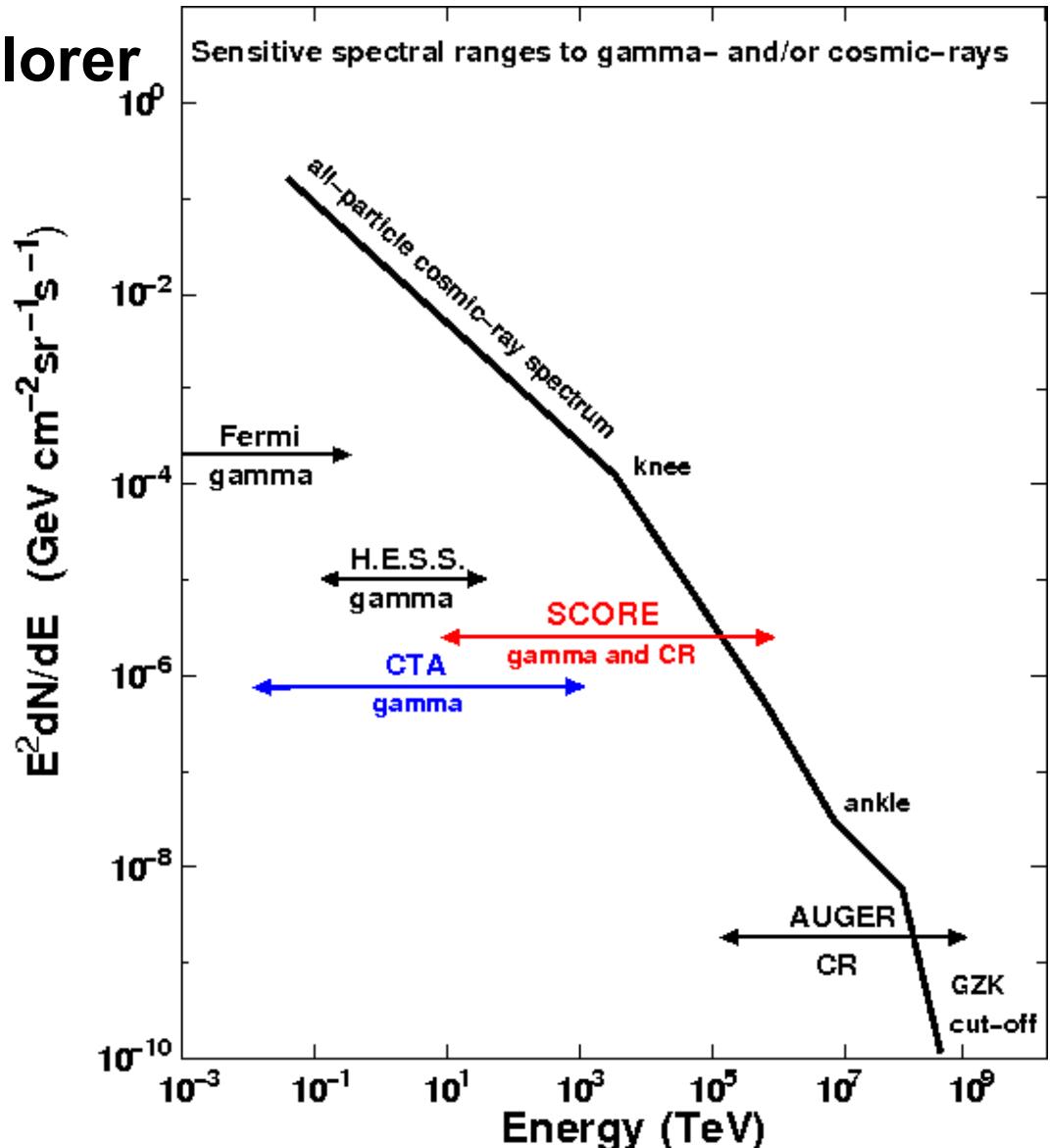
The aim of SCORE

- Study for a Cosmic ORigin Explorer
- Ultra High energies
 - Gamma-rays: $E > 10 \text{ TeV}$
 - Cosmic-rays:
 $100 \text{ TeV} < E < 1 \text{ EeV}$
- Large area: 10 km^2
- Large Field of view: 1 sr



Roadmap phase I:
“recommendation for
development of ground-based
wide-angle gamma-ray
detectors”

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— SCORE: Physics and Concept — MPPMU group meeting, October 2009

The aim of SCORE

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- Ultra High energies

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

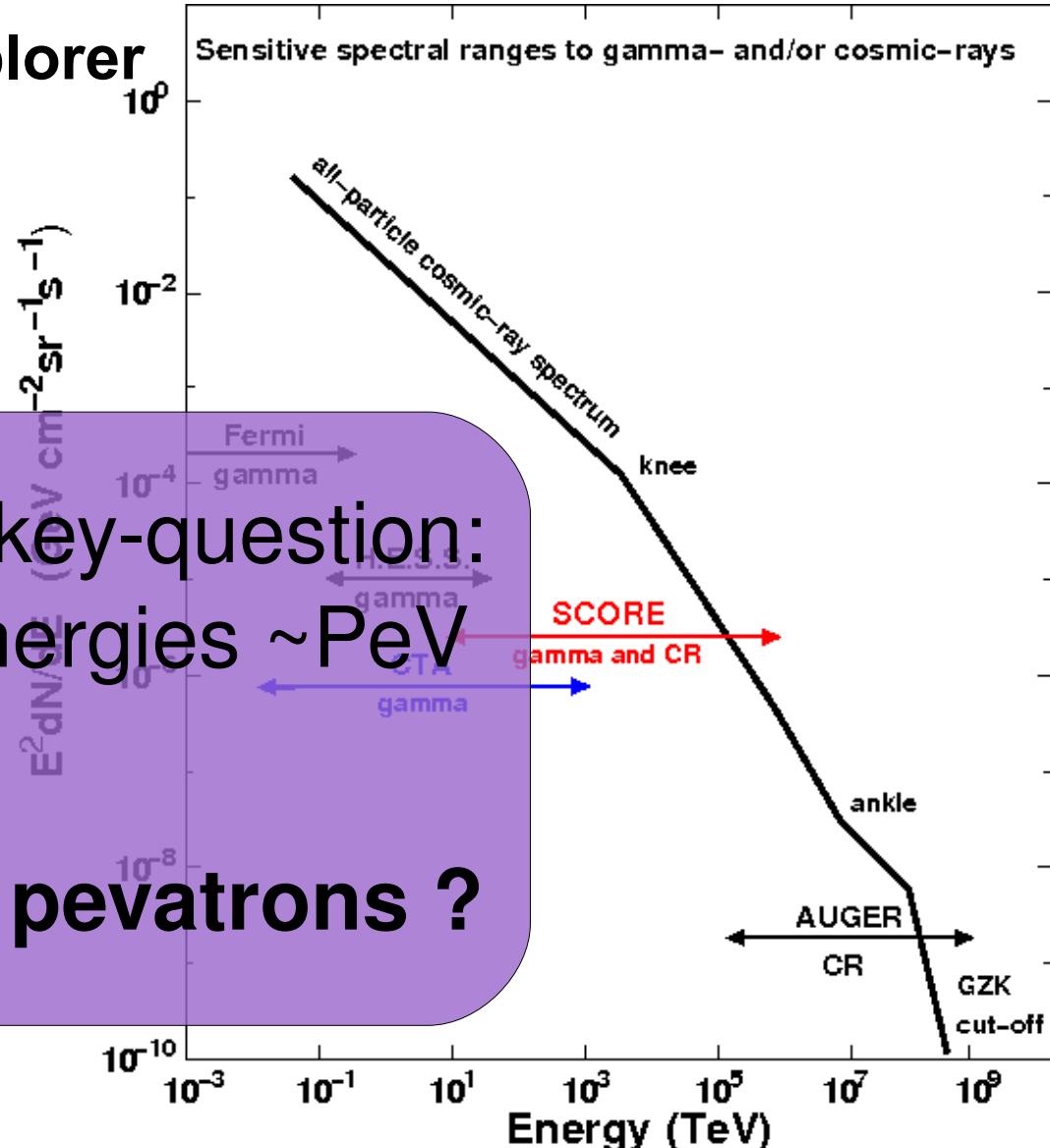
$100 \text{ TeV} < E < 1 \text{ EeV}$

- Origin of cosmic rays – key-question:
- Acceleration to knee-energies $\sim \text{PeV}$

Roadmap phase I:
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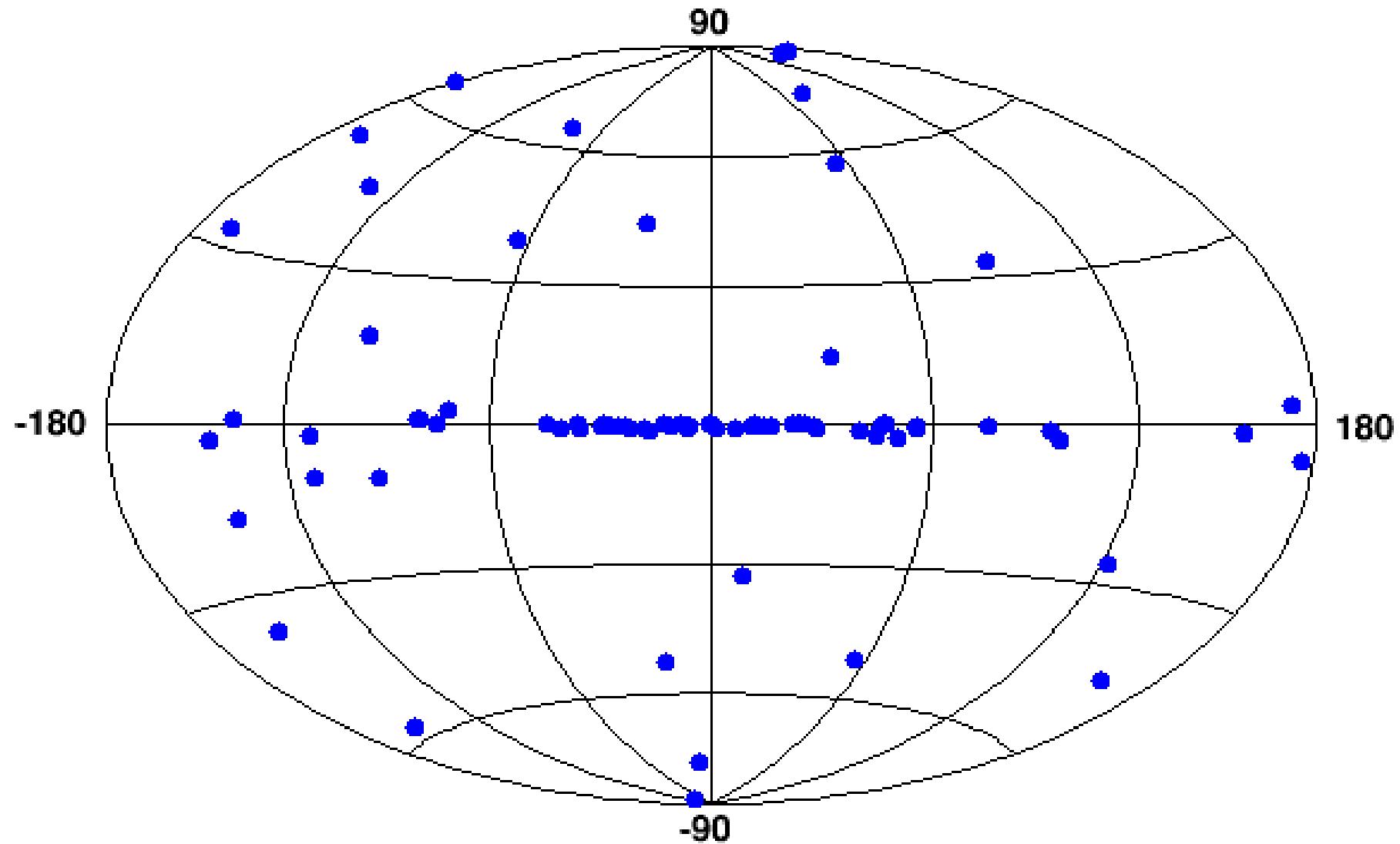
ASPERA

martin.tluczykont@desy.de — SCORE: Physics and Concept — MPPMU group meeting, October 2009



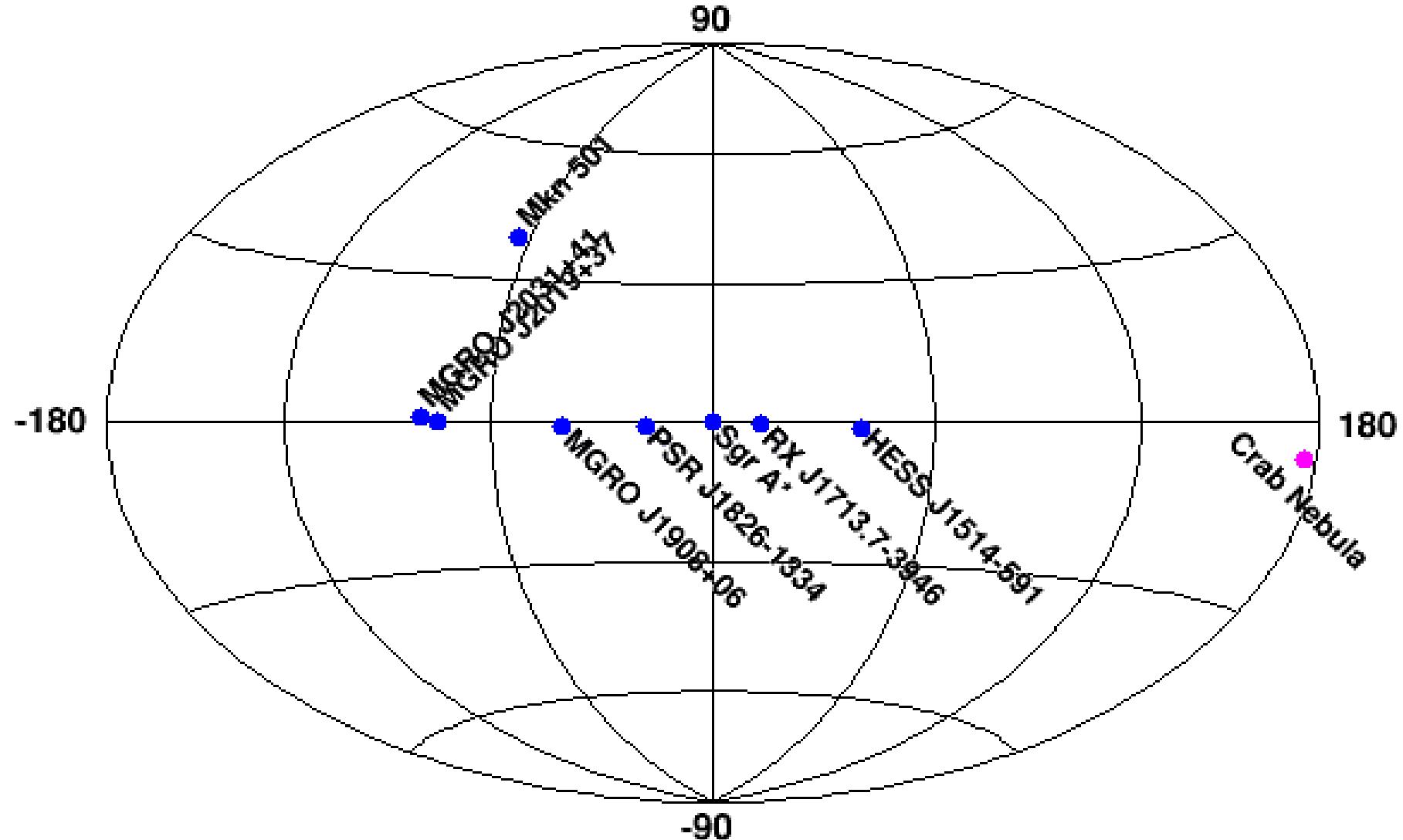
Gamma-Ray Sky

VHE gamma-ray sky 2009



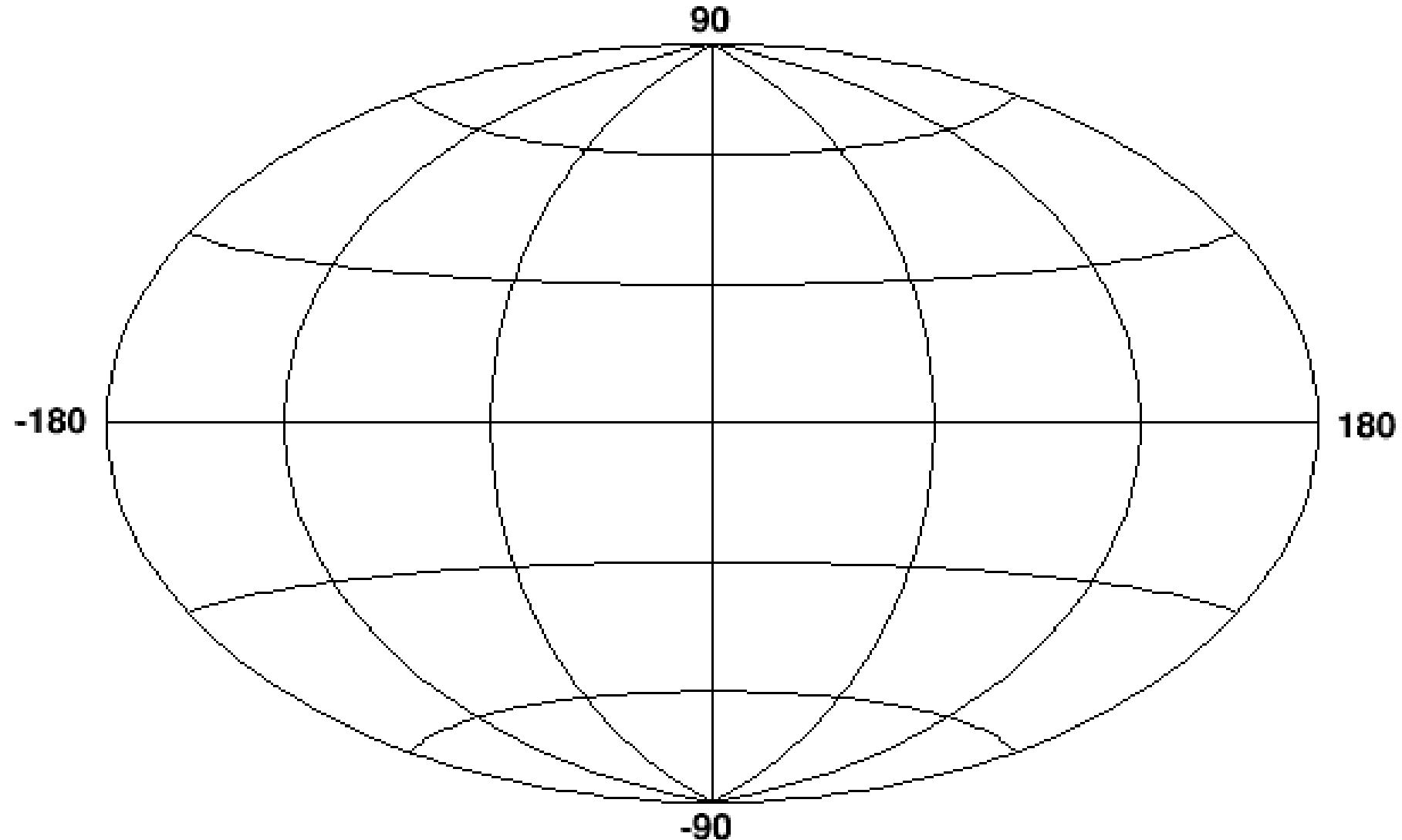
Gamma-Ray Sky

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



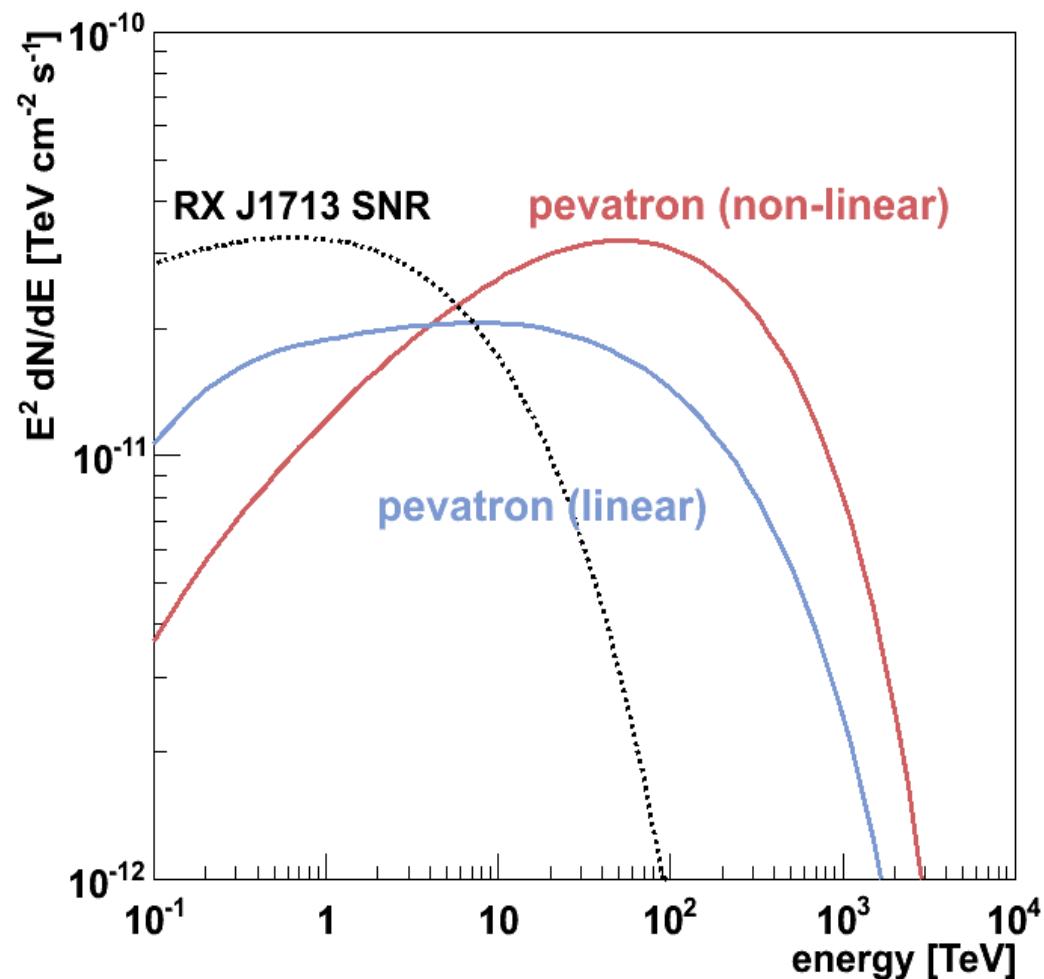
Gamma-Ray Sky

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



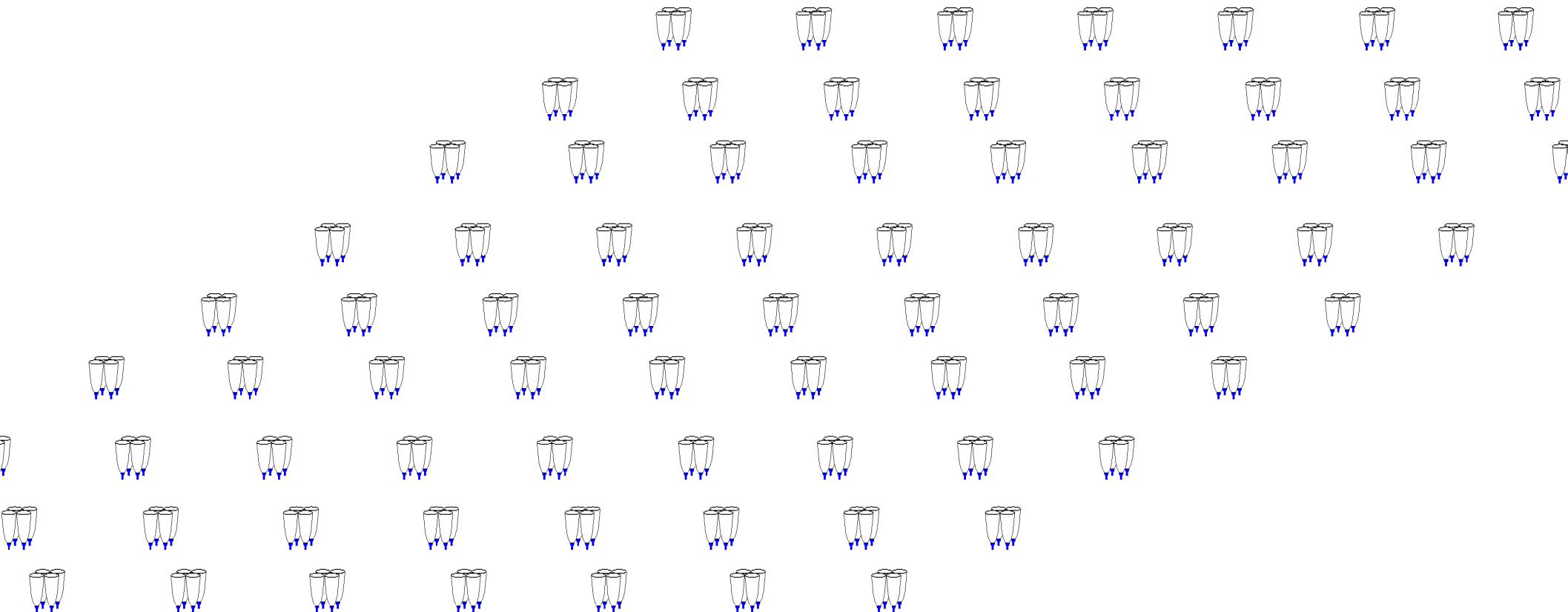
Where are the cosmic pevatrons ?

The main goal of SCORE



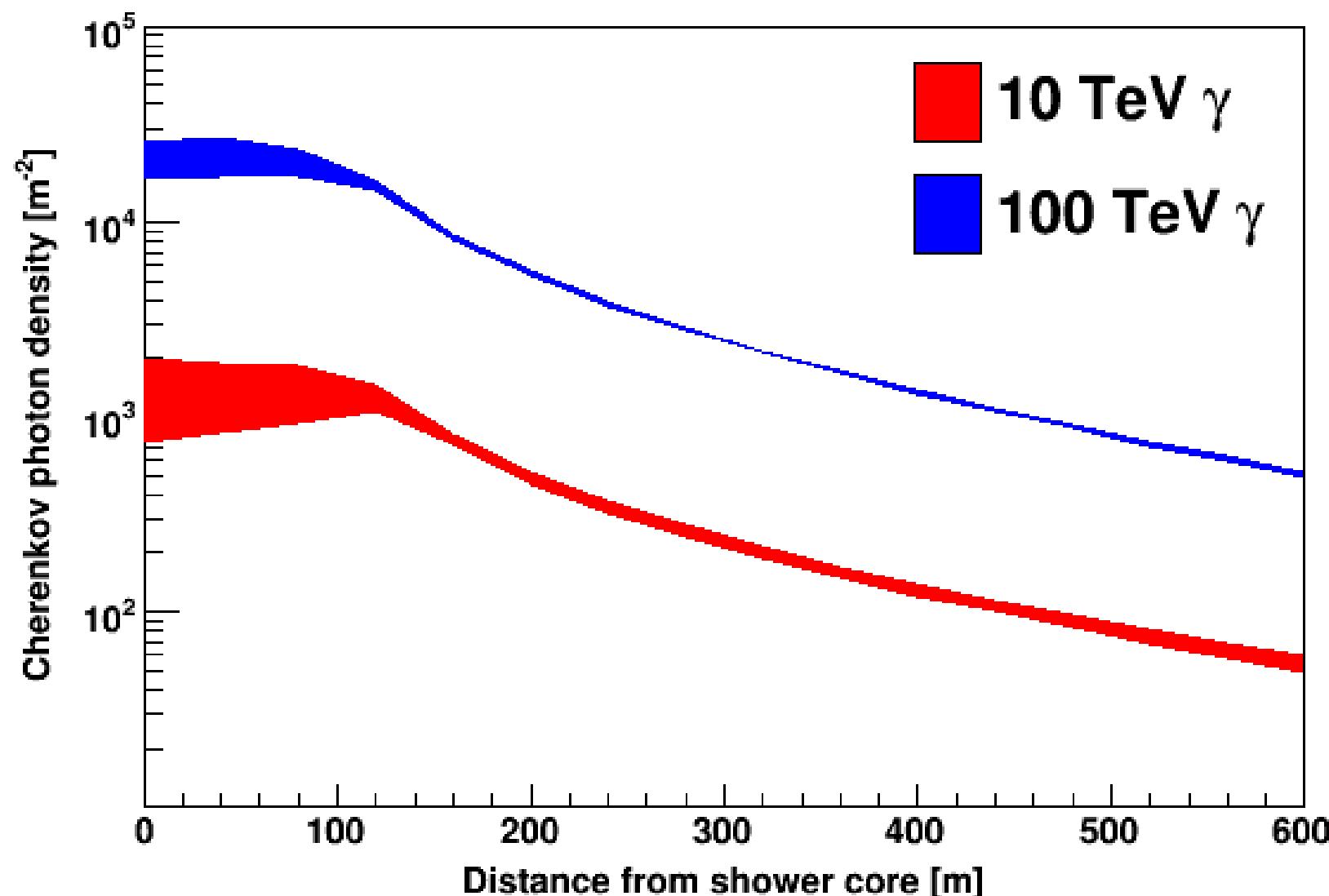
The SCORE principle

- Ultra-High energy regime: **large effective area !**
- Imaging ACTs: ~ 25000 channels / km^2
- **Use non-imaging Cherenkov technique: Shower-front sampling**
SCORE: < 200 channels / km^2

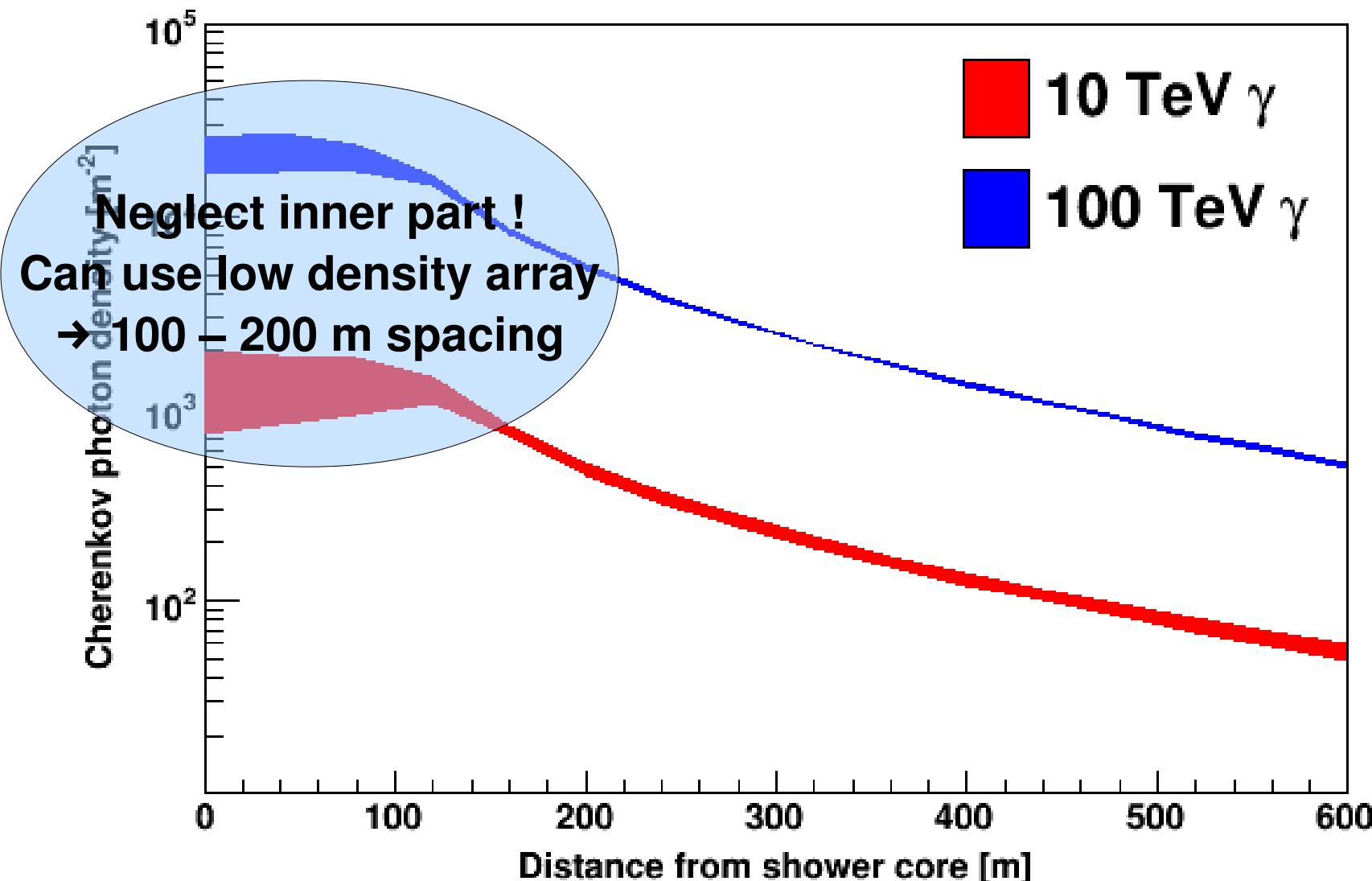


A look at the lateral photon distribution...

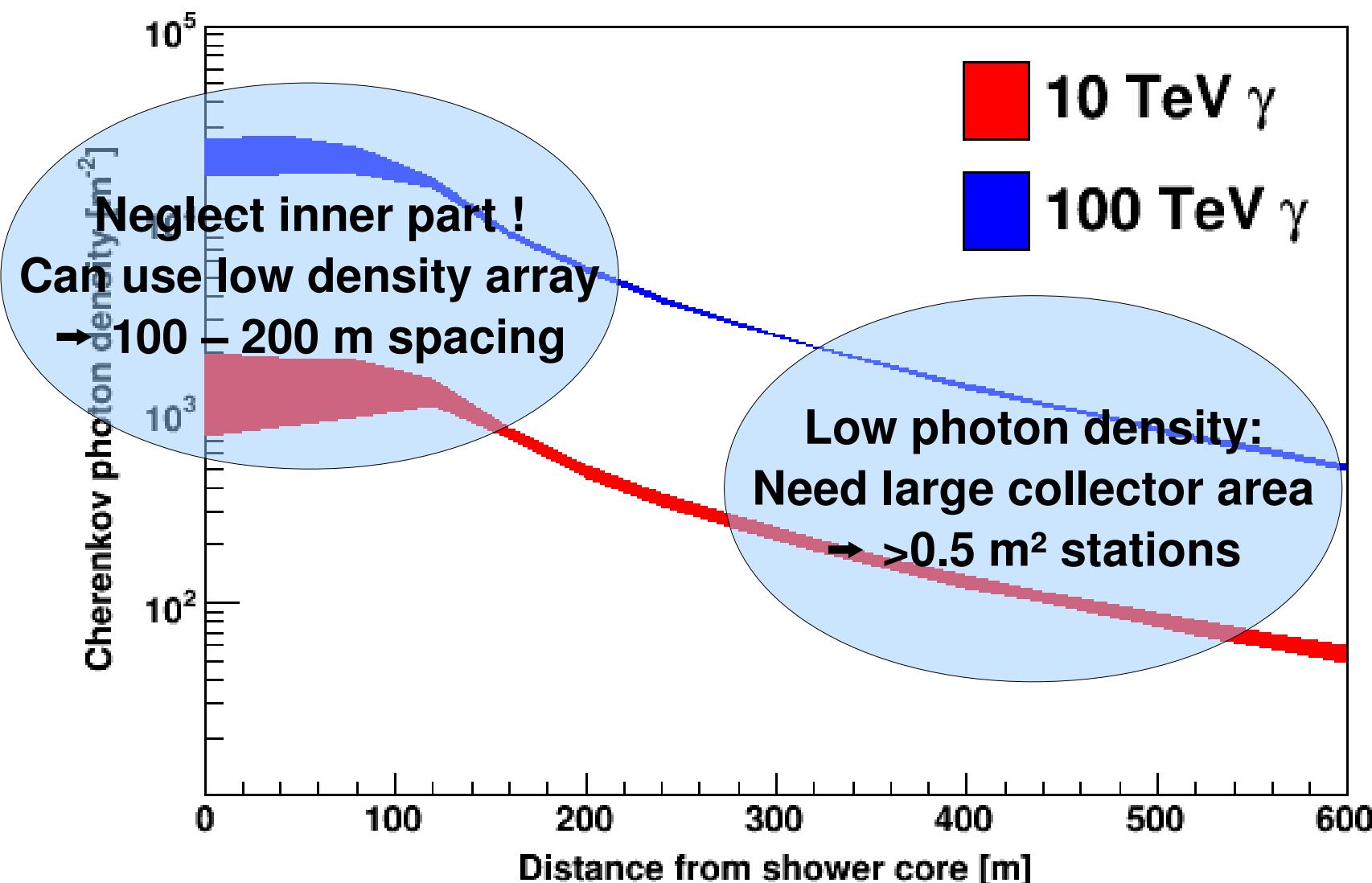
Lateral Cherenkov Photon Distribution



Lateral Cherenkov Photon Distribution

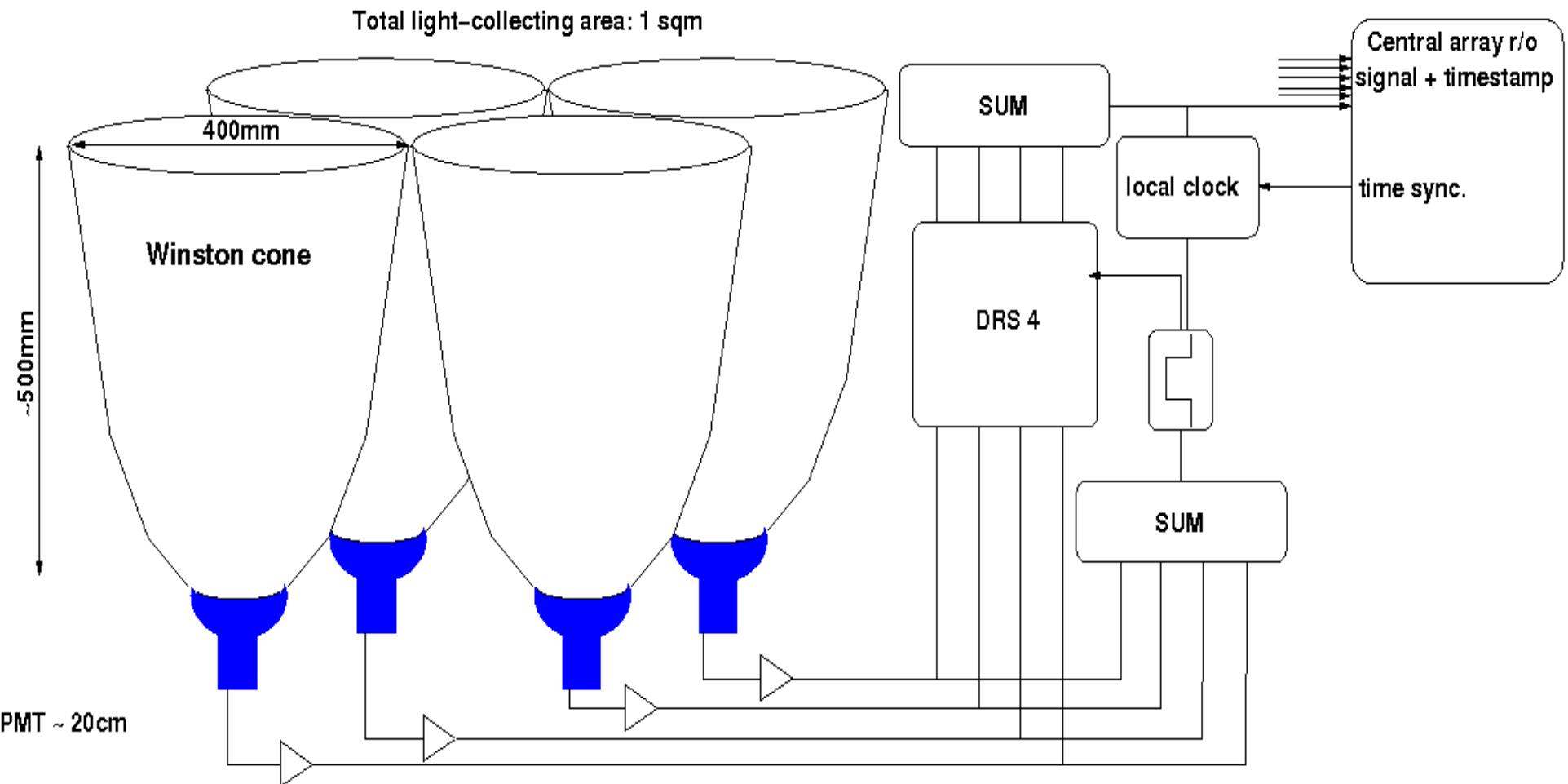


Lateral Cherenkov Photon Distribution

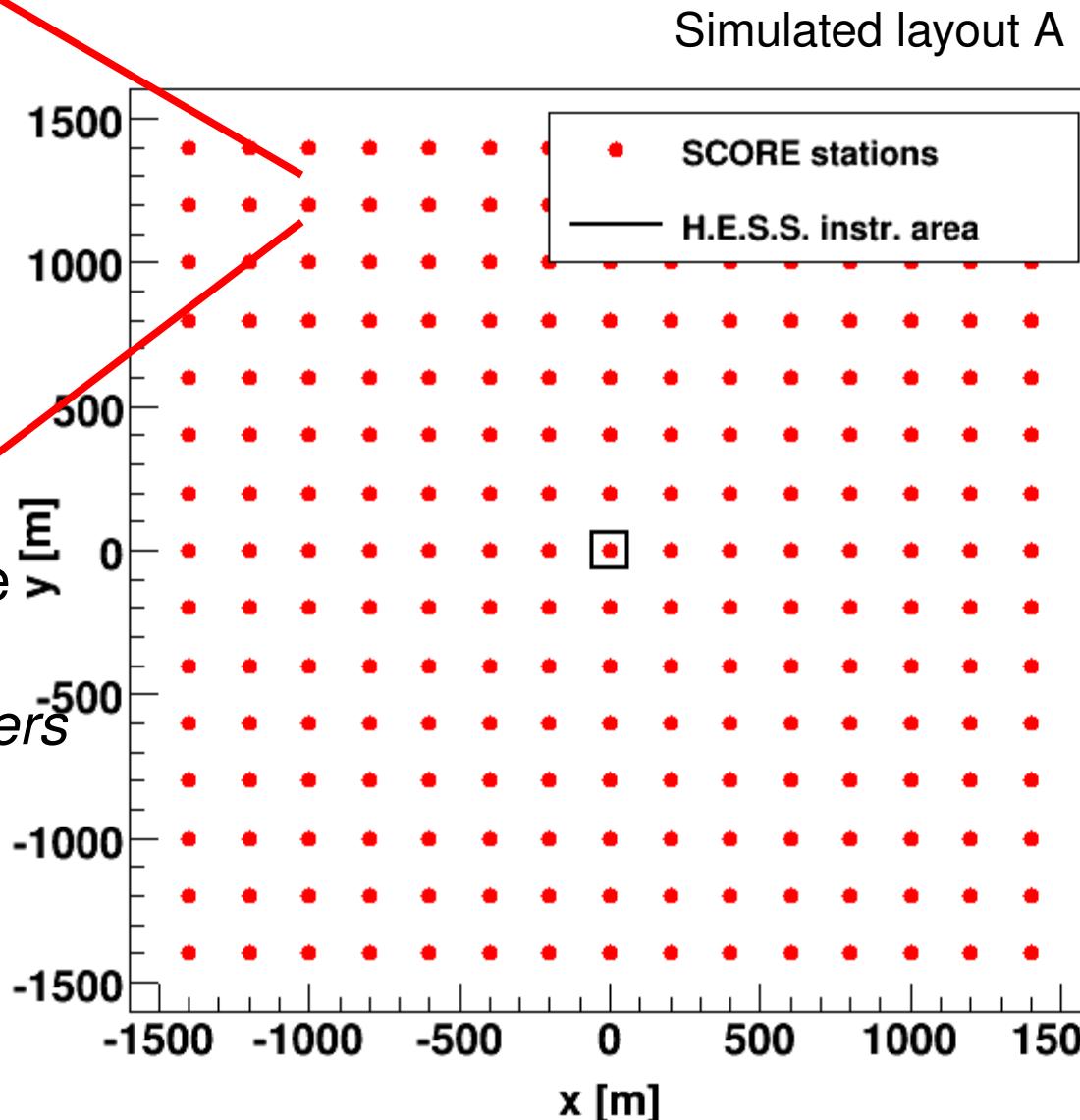
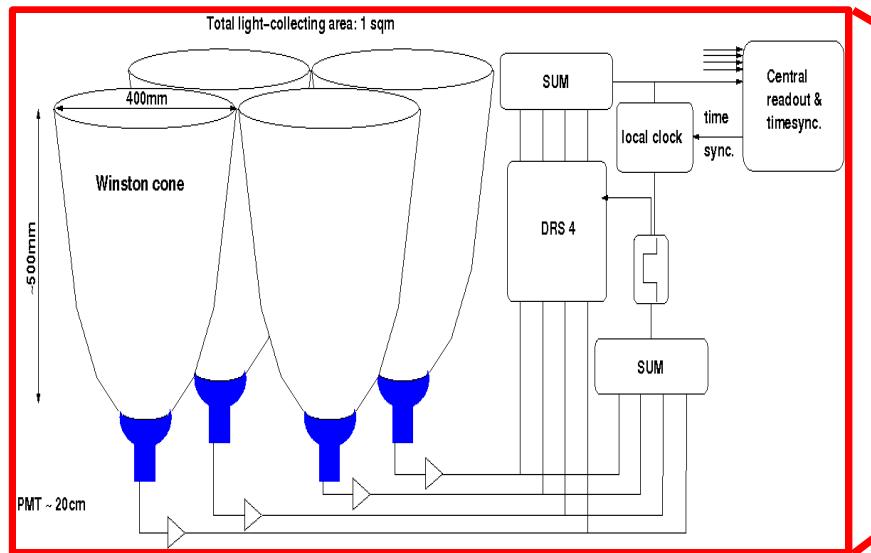


SCORE Detector Station

- Low photon density: large station area
- 2 – 4 channel station trigger coincidence: NSB suppression



SCORE Detector Array

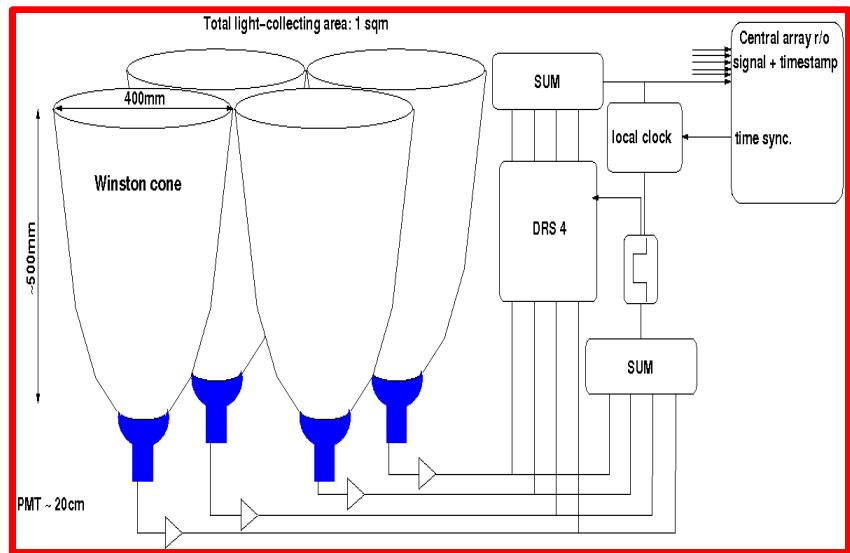


Station trigger: 4-channel coincidence

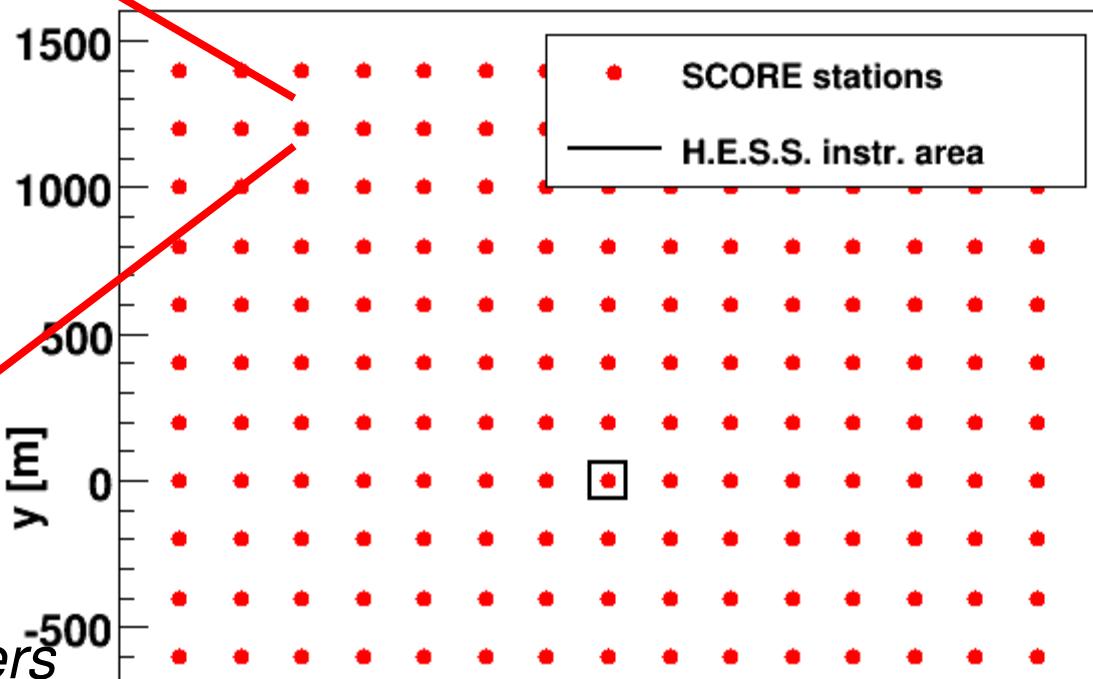
Array trigger: 2-station coincidence

Distribute over sub-array *cluster triggers*

SCORE Detector Array



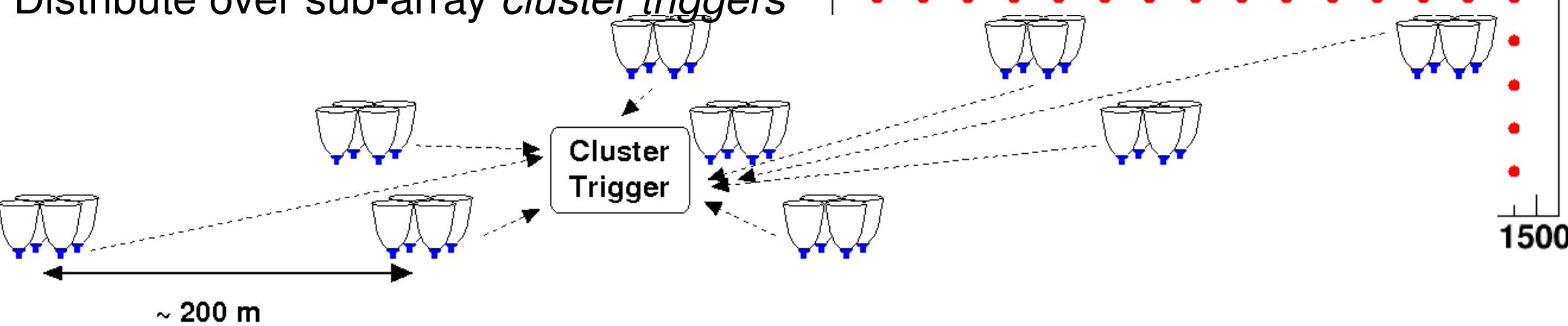
Simulated layout A



Station trigger: 4-channel coincidence

Array trigger: 2-station coincidence

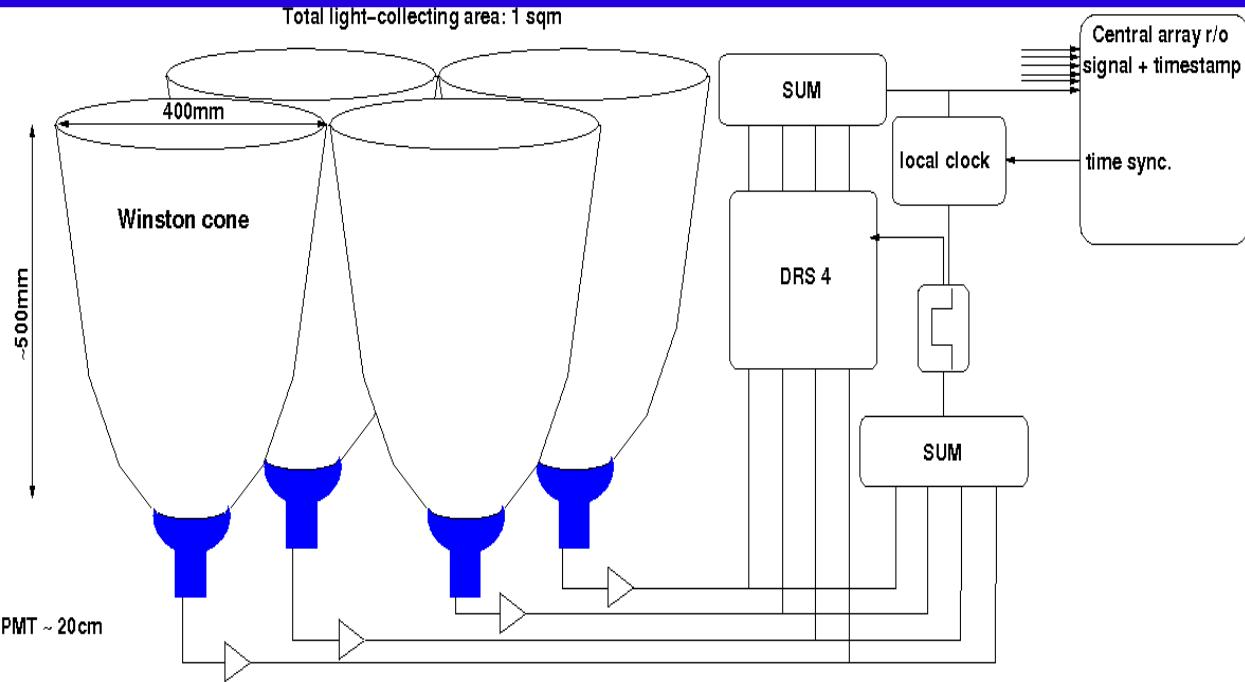
Distribute over sub-array *cluster triggers*



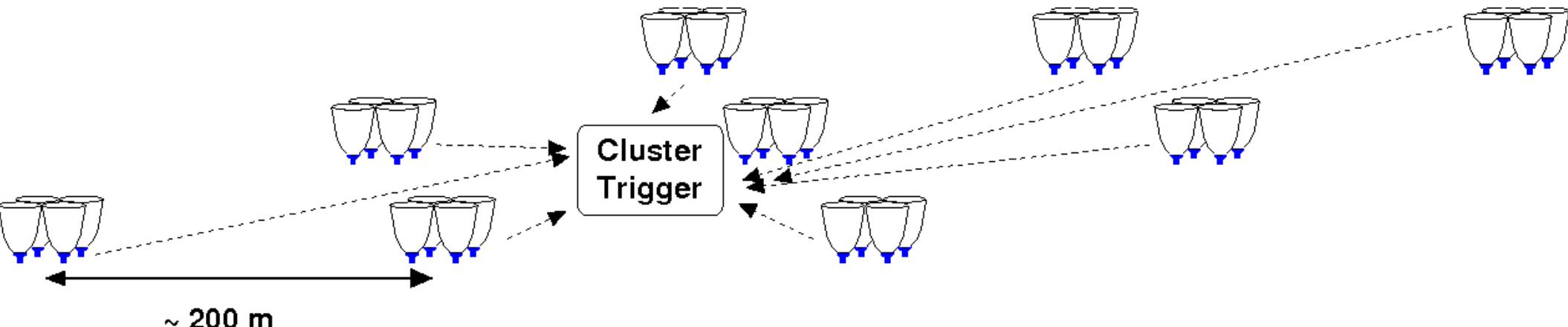
Trigger levels

1) Local station trigger:

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

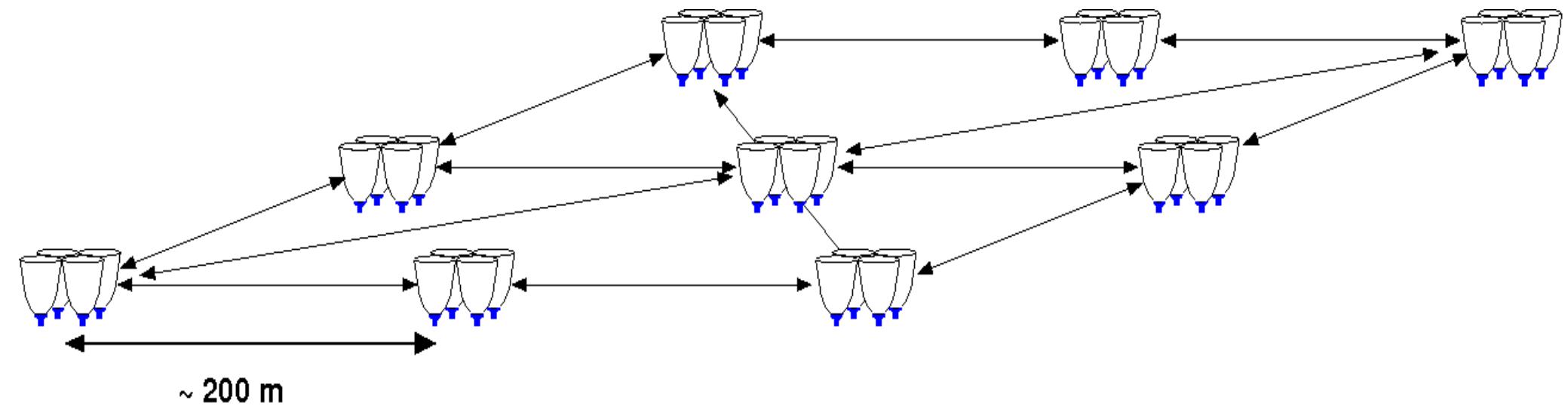


2) Array trigger: next-neighbour station trigger ($\Delta t = 1\mu\text{s}$)



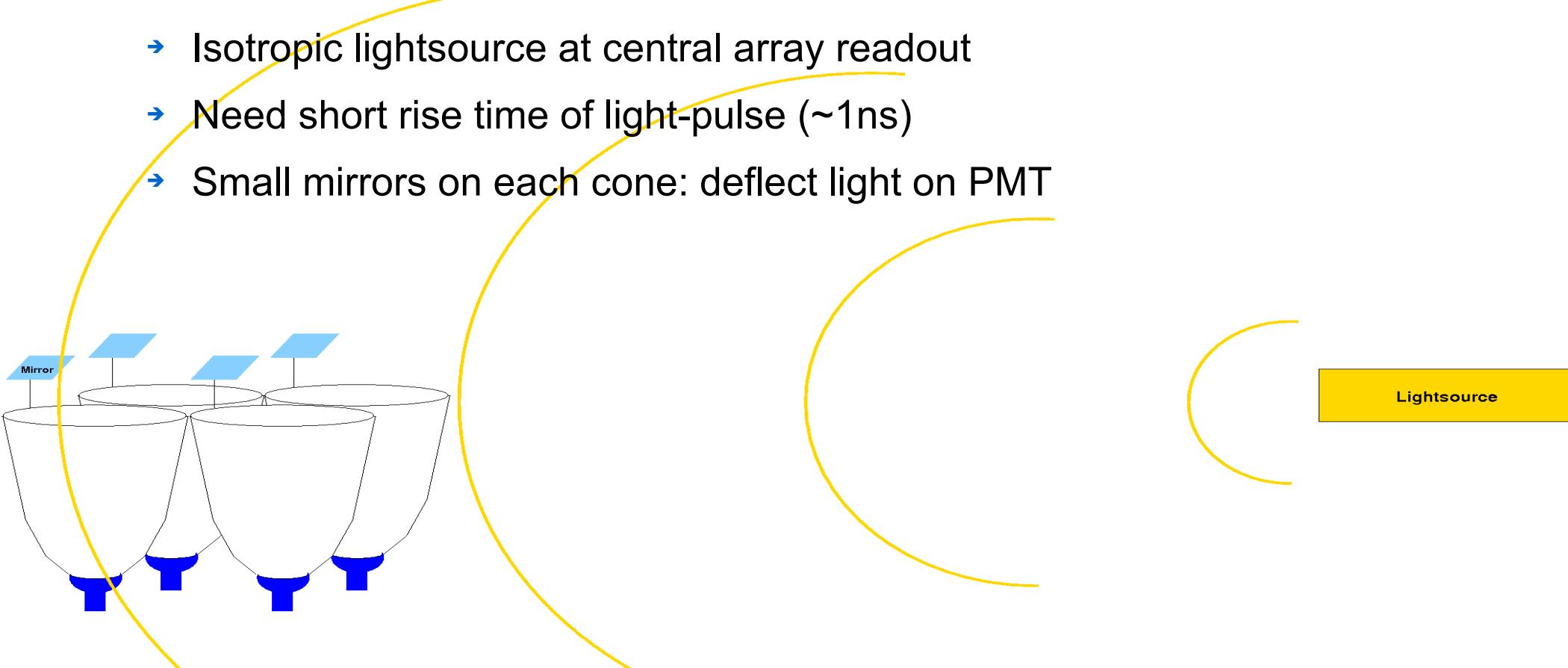
Smart Array Trigger

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



Time Synchronization

- Need < 5ns timestamp accuracy
- GPS is no option: 10 ns
- Optical fibers: expensive
- Alternative: **Lightsource synchronization:**
 - Isotropic lightsource at central array readout
 - Need short rise time of light-pulse (~1ns)
 - 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”

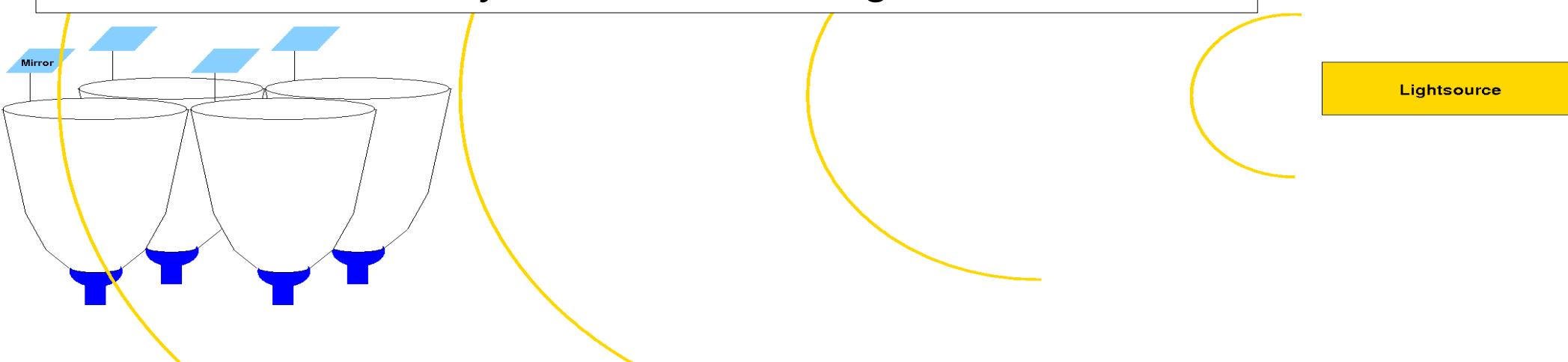
$T = T_s + 10\text{ns}$

Send light-pulse

Station triggered by light pulse

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

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



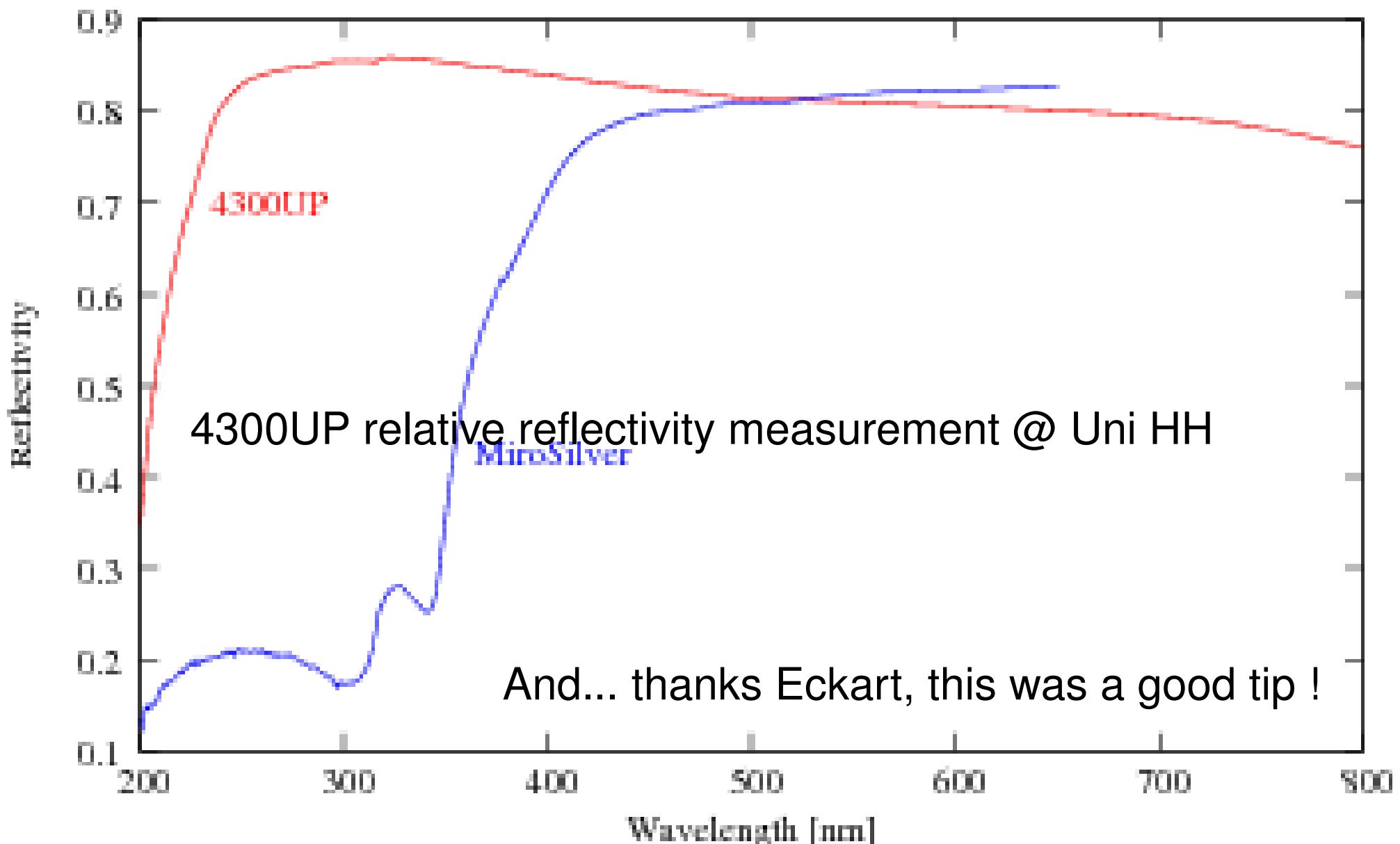
SCORE Detector Array

- Layout A:
 - Station spacing 200 m
 - Station area $\sim 1 \text{ m}^2$ (Cone entrance)
 - Field of view 0.85 sterad (30° 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

- **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 test unit
- Currently building PMT test bed
- Planning prototype deployment on DESY site (closed stations w/ scintillator)
- Other setup for NSB measurement:
RP580 PMTs, discriminator + ADC/scaler for NSB photon count

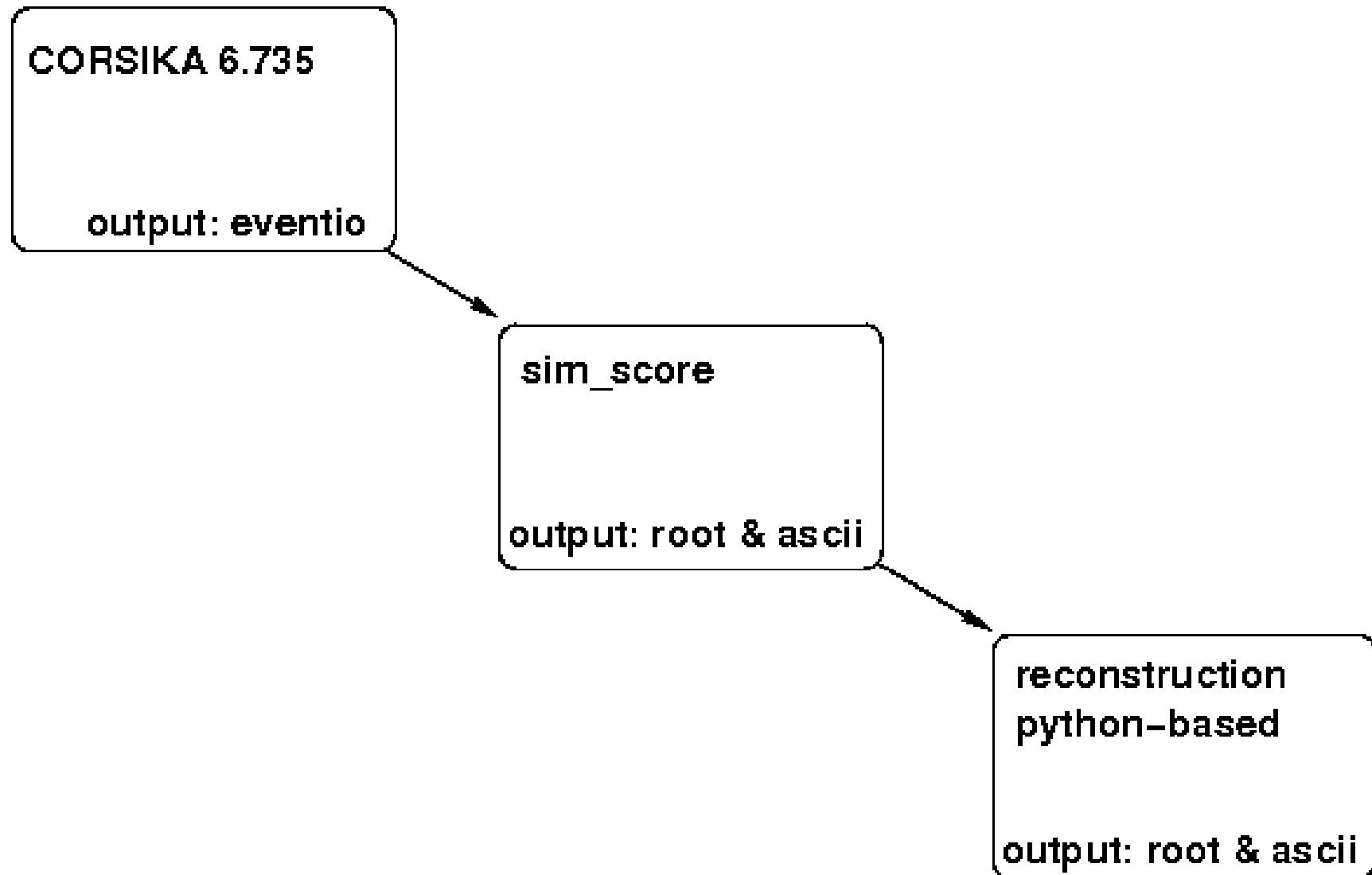
Hardware Prototyping / Testing



SCORE Detector Simulation

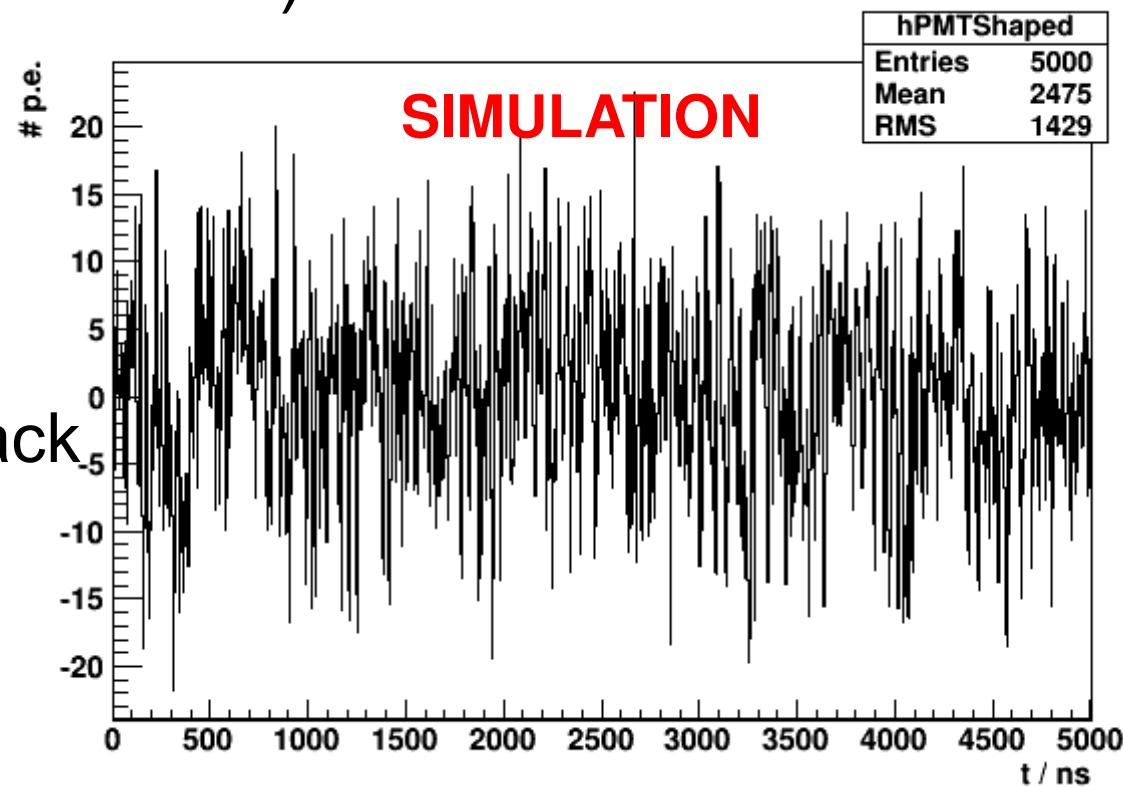
- Shower simulation: CORSIKA 6.735
- Detector simulation: sim_score
 - Based on iact package (K. Bernlöhr, sim_skeleton.c)
 - Atmospheric transmission: MODTRAN
 - Tabulated Winston Cone acceptance (ray traced)
 - Tabulated PMT QE = $\text{QE}(\lambda)$ (manufacturer)
 - Pulse shaping: Pulse shape as in V. Henke, Dipl. Thesis
 - Trigger: Next-Neighbour array trigger (1 μs 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)

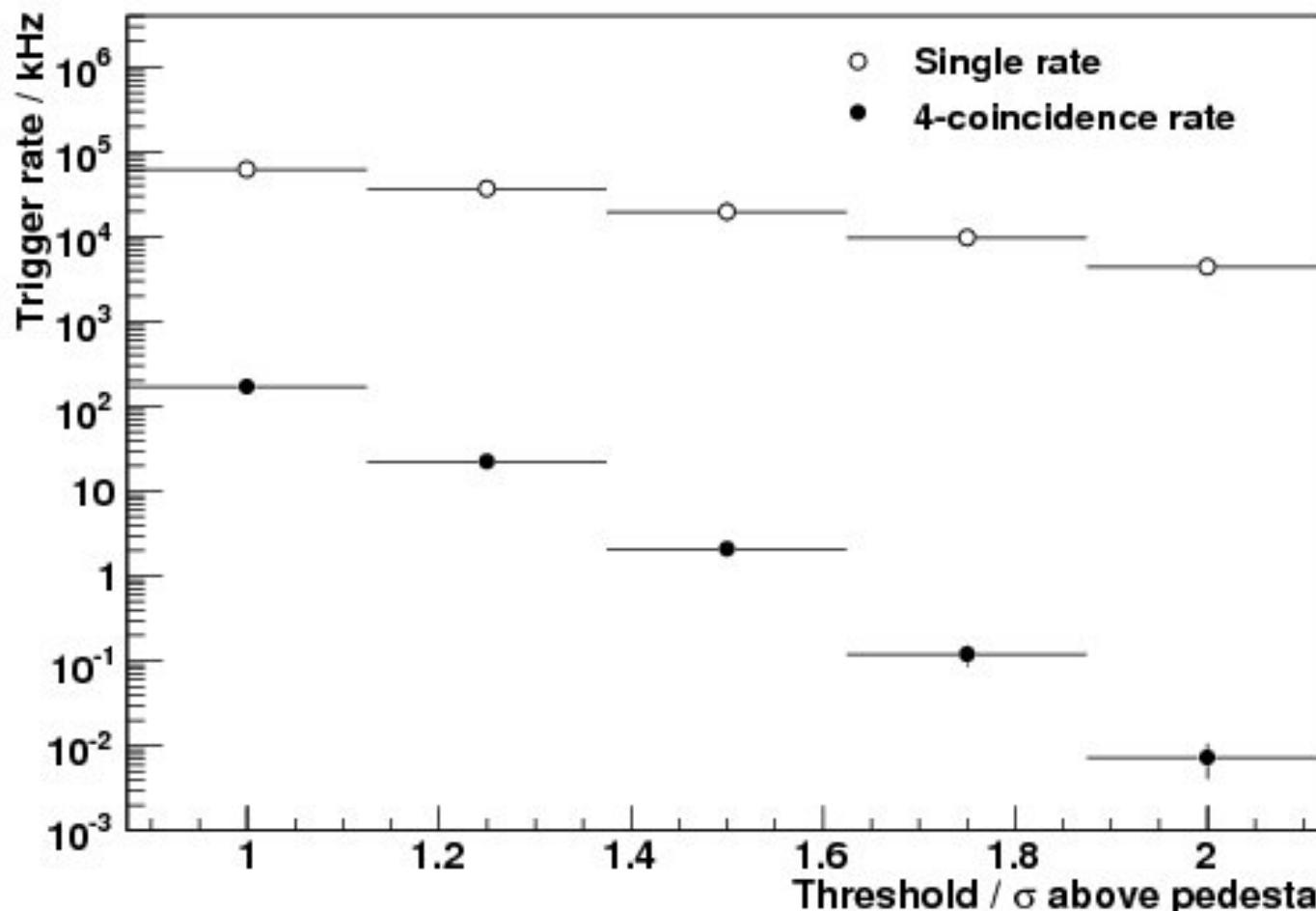


NSB in Australia

- 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



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

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

$$R_{\text{NSB}} = 2e12 / \text{m}^2 \text{ s sr}$$

Shower depth reconstruction: Improve S/N: station stacking

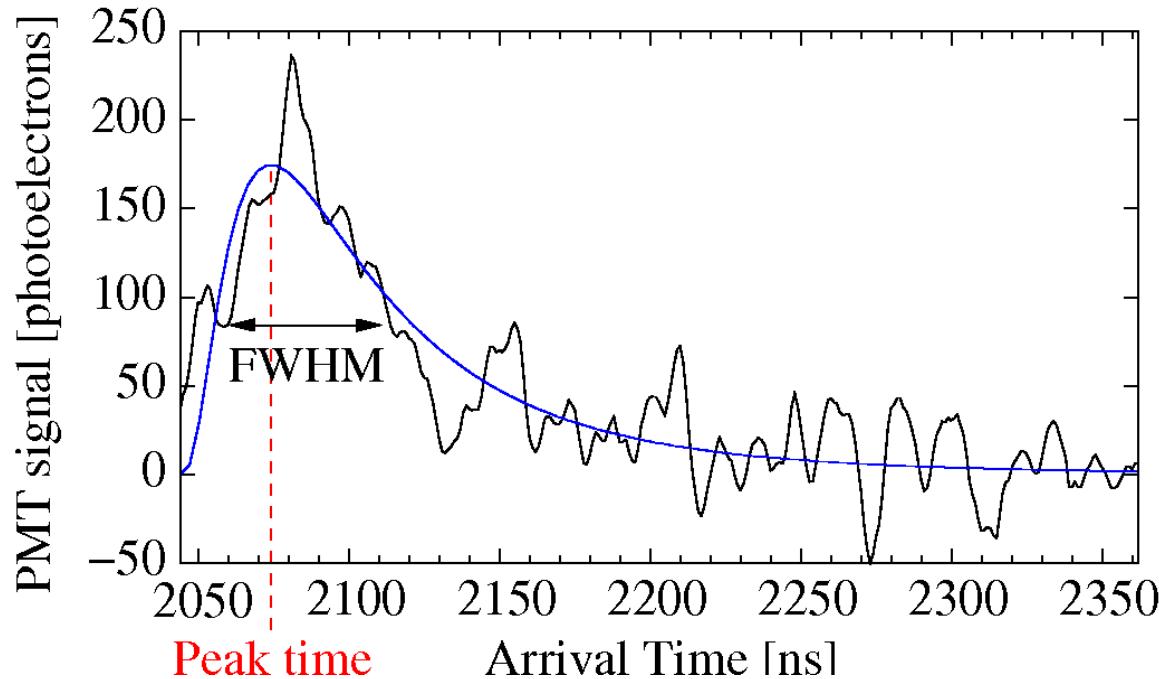
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Expected Trigger Rates

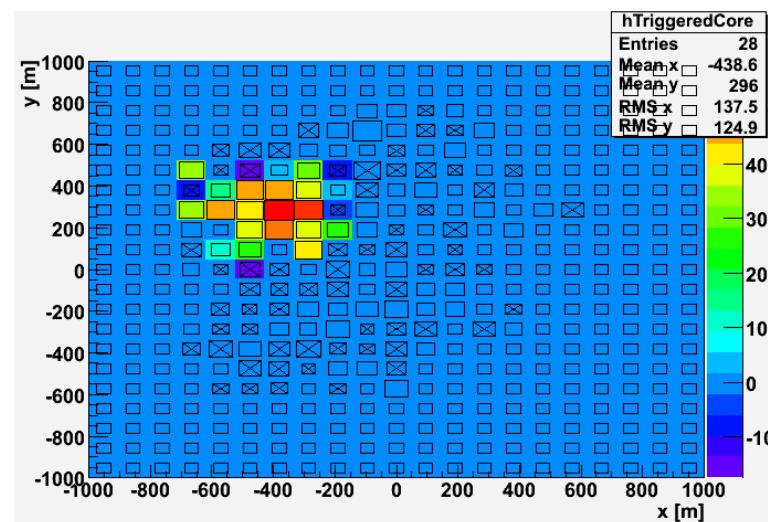
- Trigger conditions:
 - 1.5 sigma above NSB per channel
 - 4-channel coincidence per station
 - 2-station coincidence (array trigger)
- NSB:
 - 4-coincidence: ~1 kHz
 - 4-coincidence @ 2 sigma above NSB: ~10 Hz
- Hadrons: $O(1 - 10 \text{ kHz})$ (depending on layout)

Reconstruction

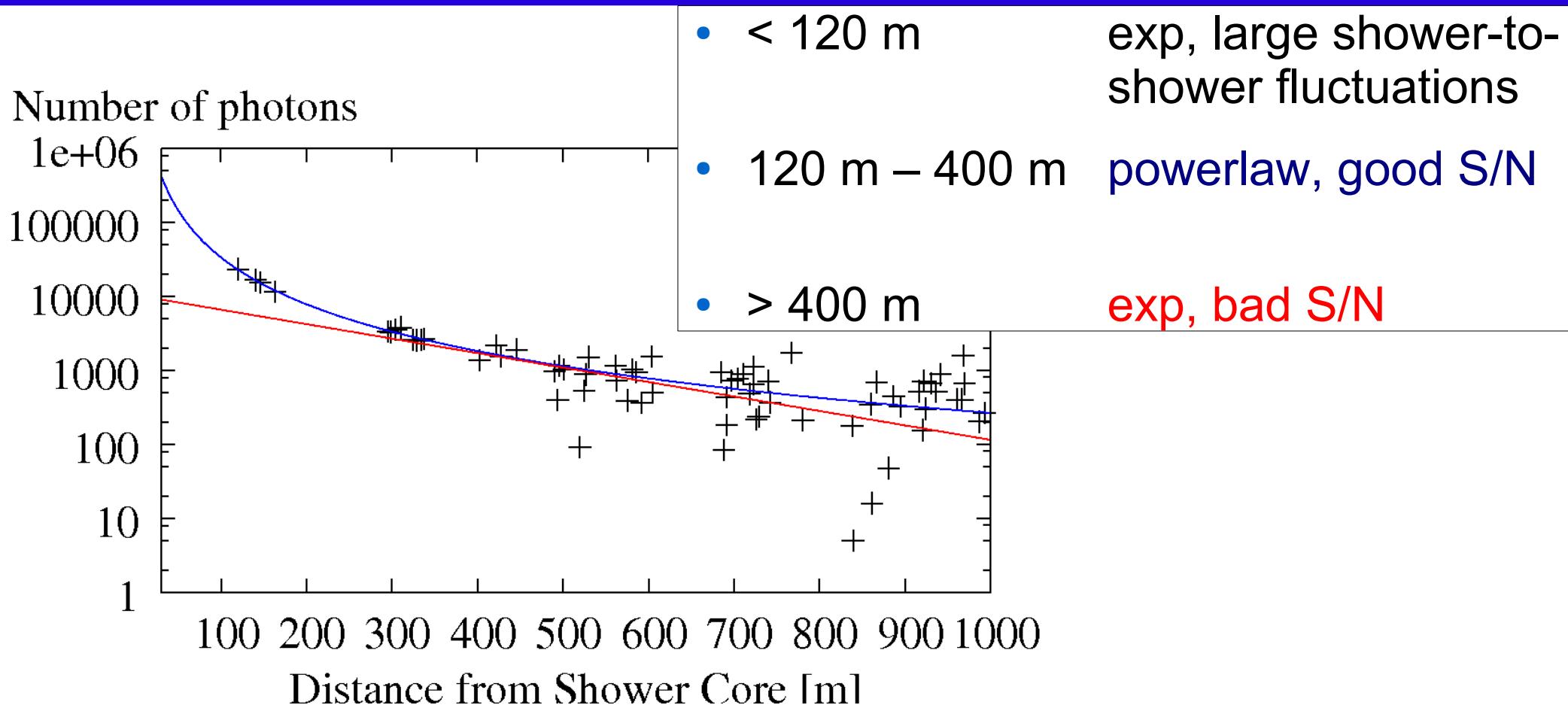
Amplitude & Timing



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

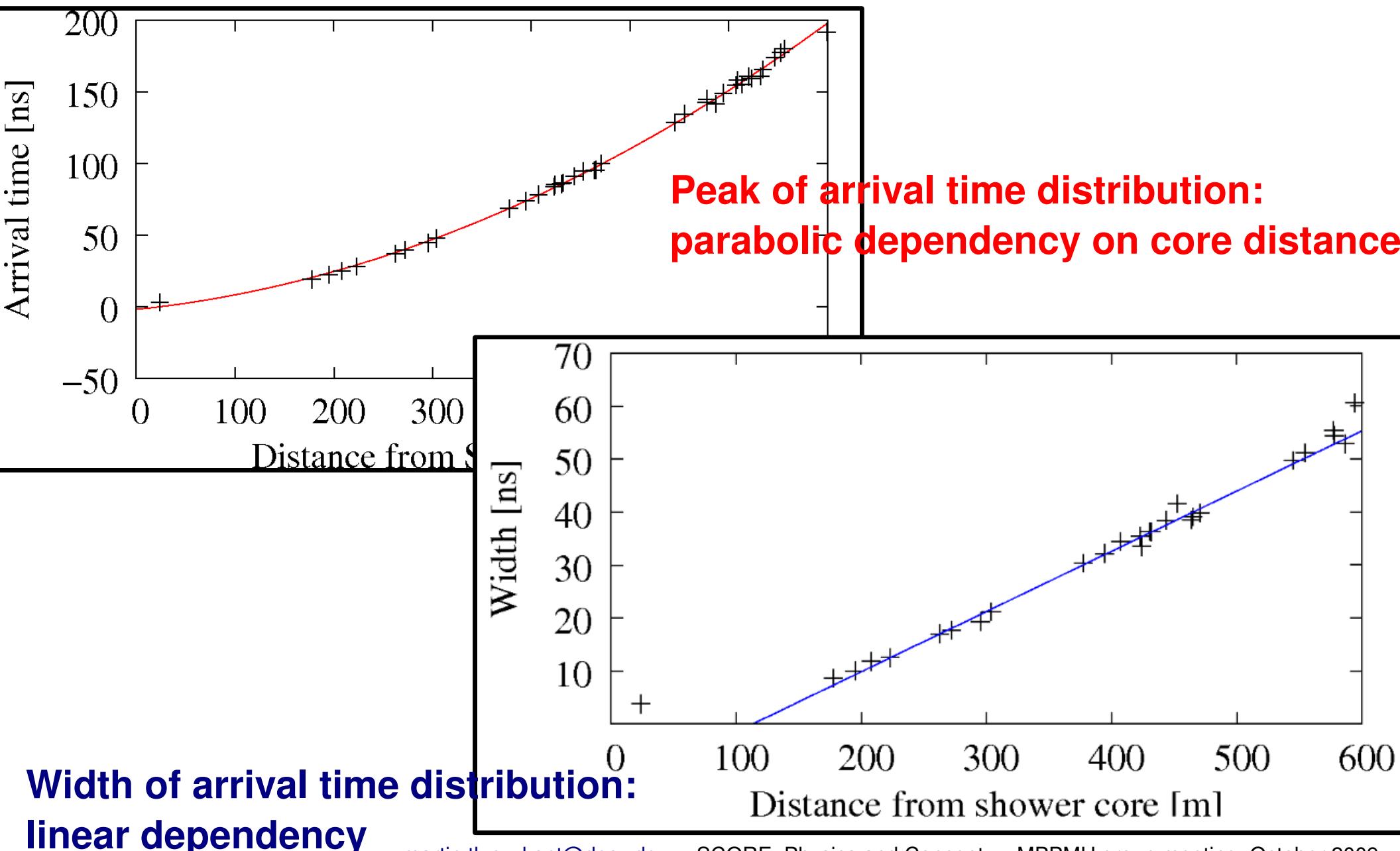


Amplitude: The Lateral Density Function



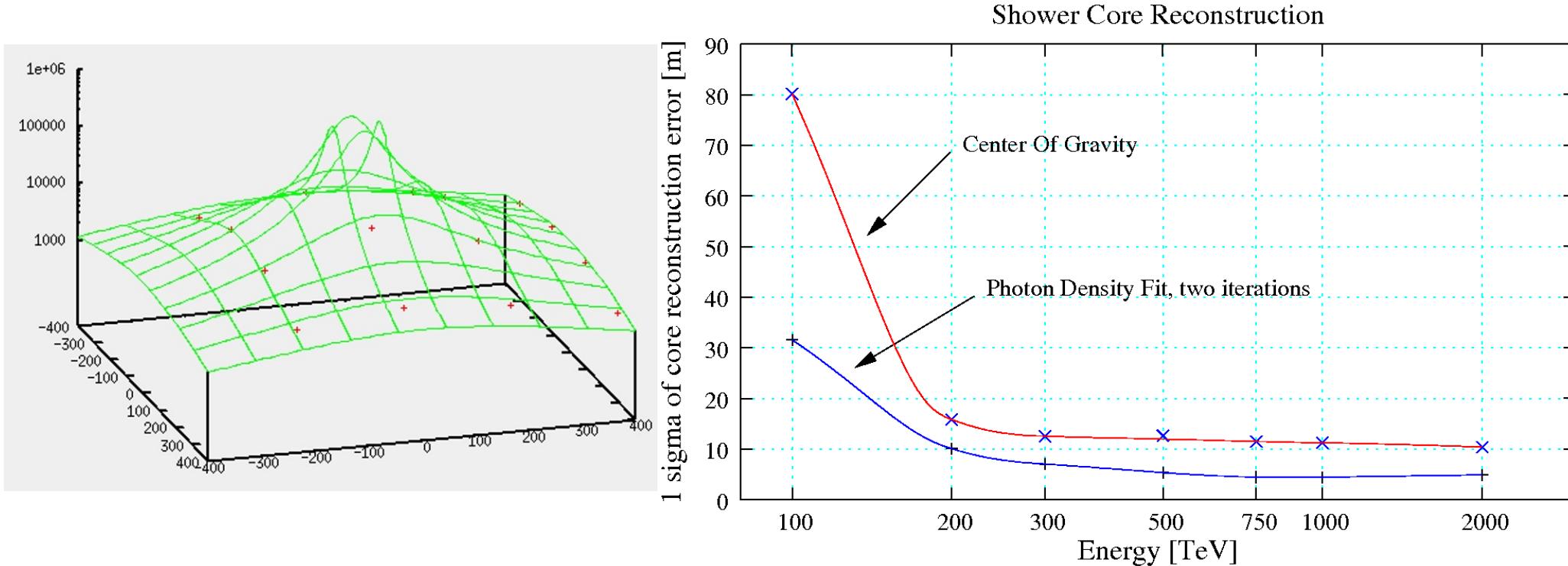
- Previous experiments: mainly inner fluctuating part
- SCORE: mainly $> 120 \text{ m}$ (powerlaw, exp)
Advantages: small shower-to-shower fluctuations, large lever arm !

Timing: Arrival Time Distribution



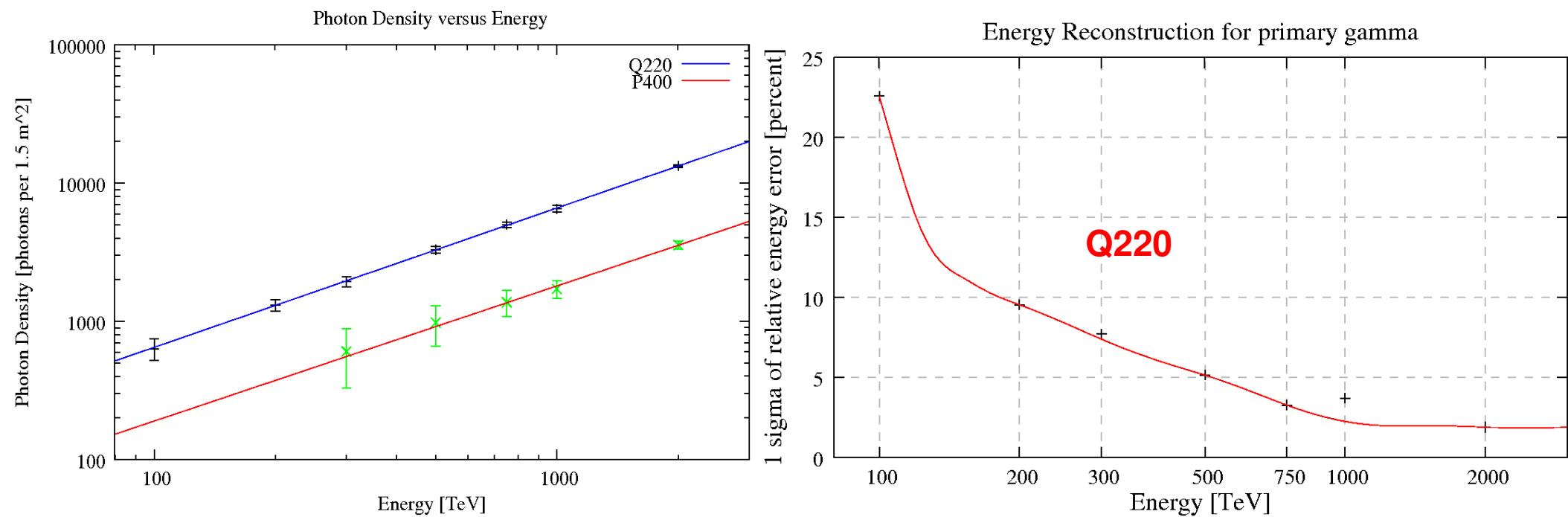
Shower Core Impact

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



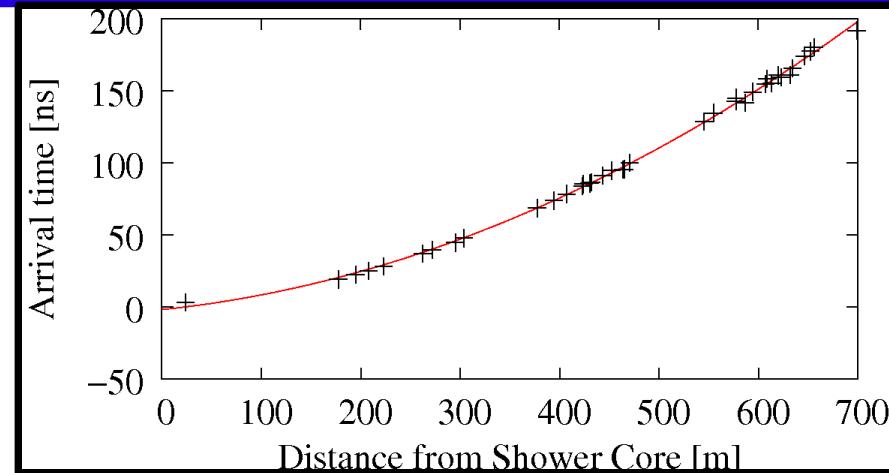
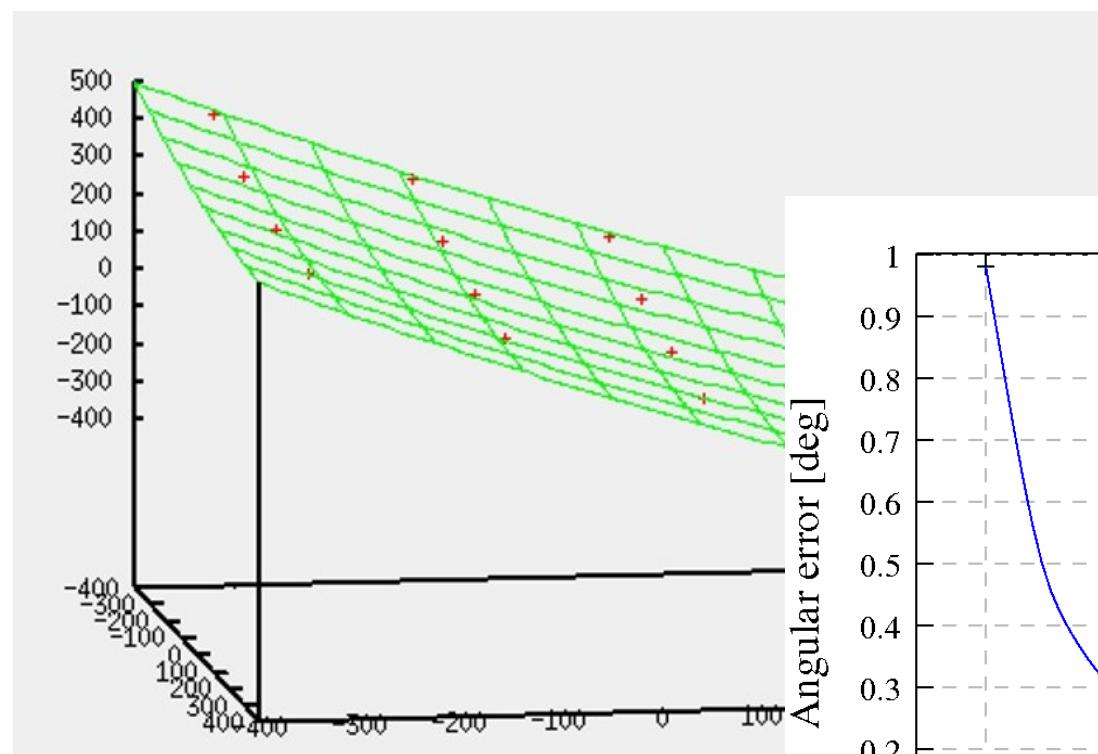
Primary Energy

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

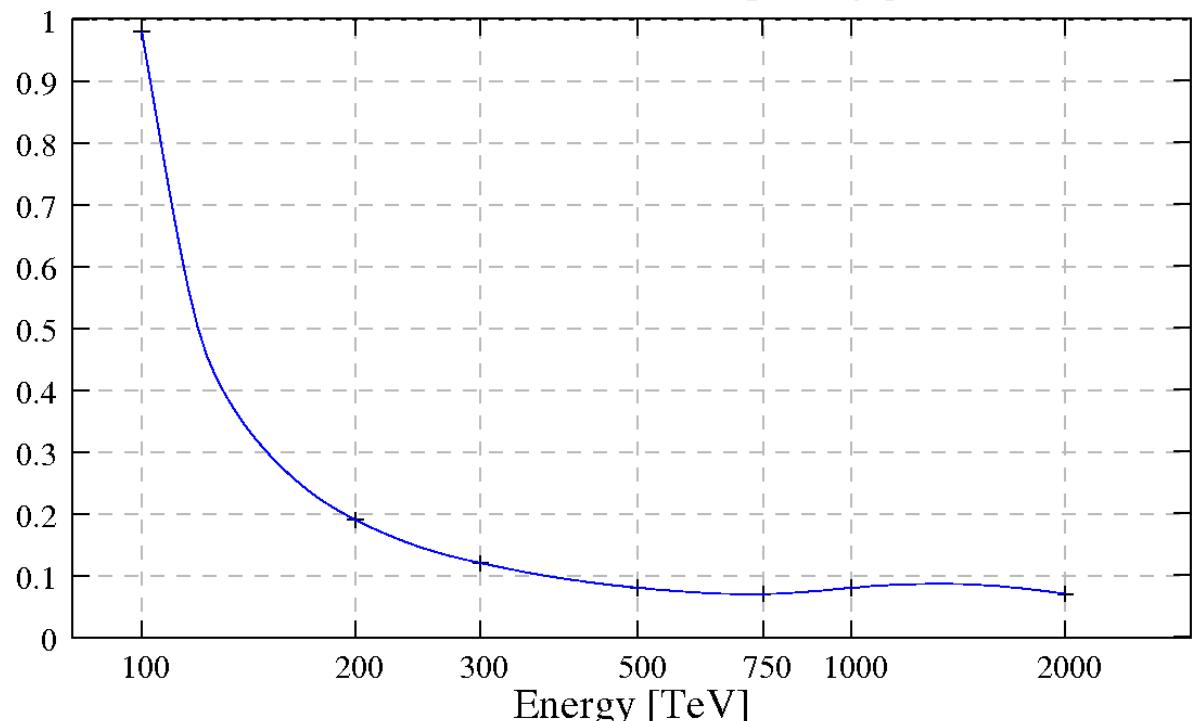


Primary Direction

Fit 2D Parabola + plane
to measured arrival times



Reconstruction of direction of primary gamma



Shower Depth

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

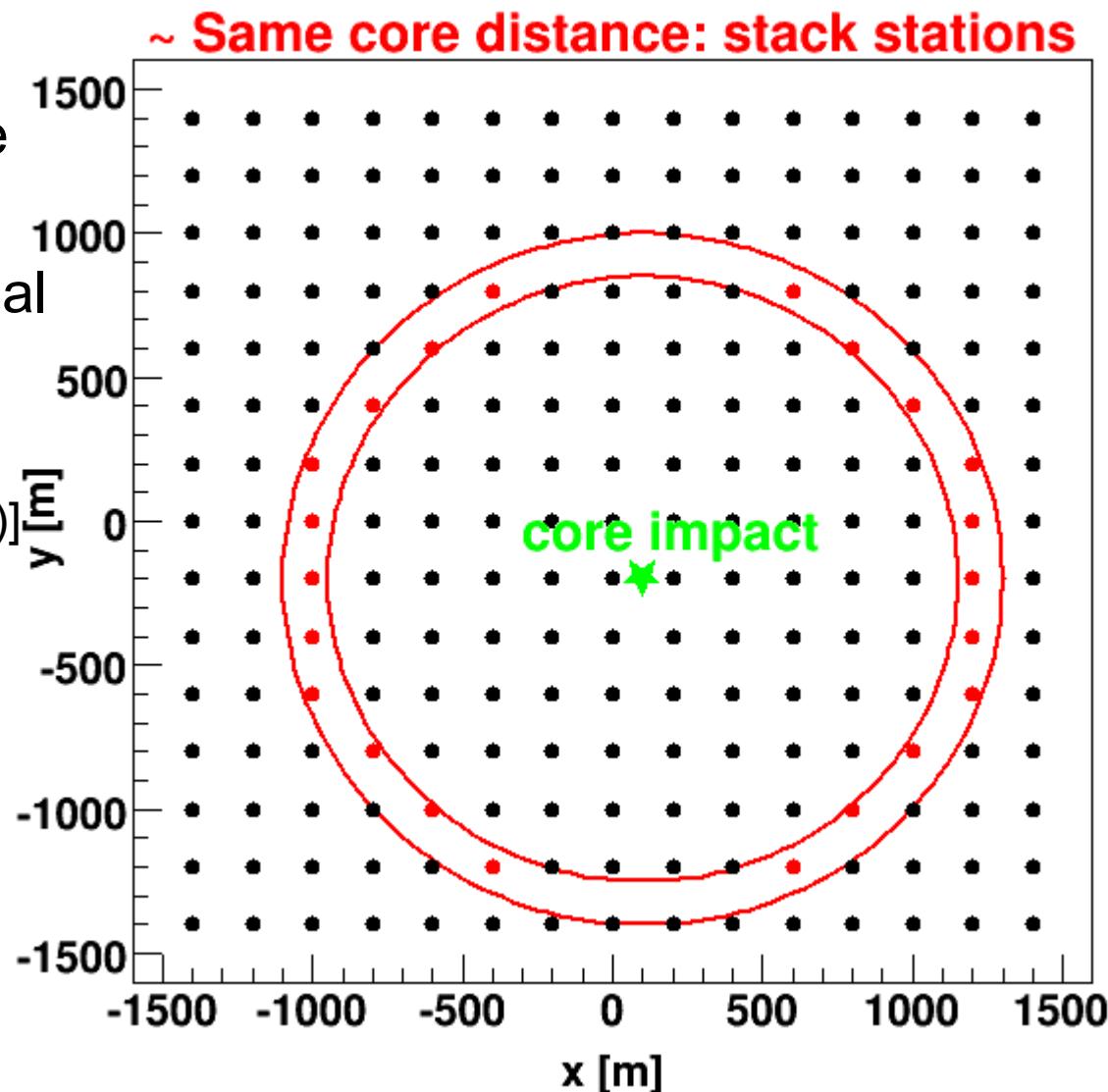
1) Stack stations with same core distance: better S/N

2) Fit log-normal function to signal

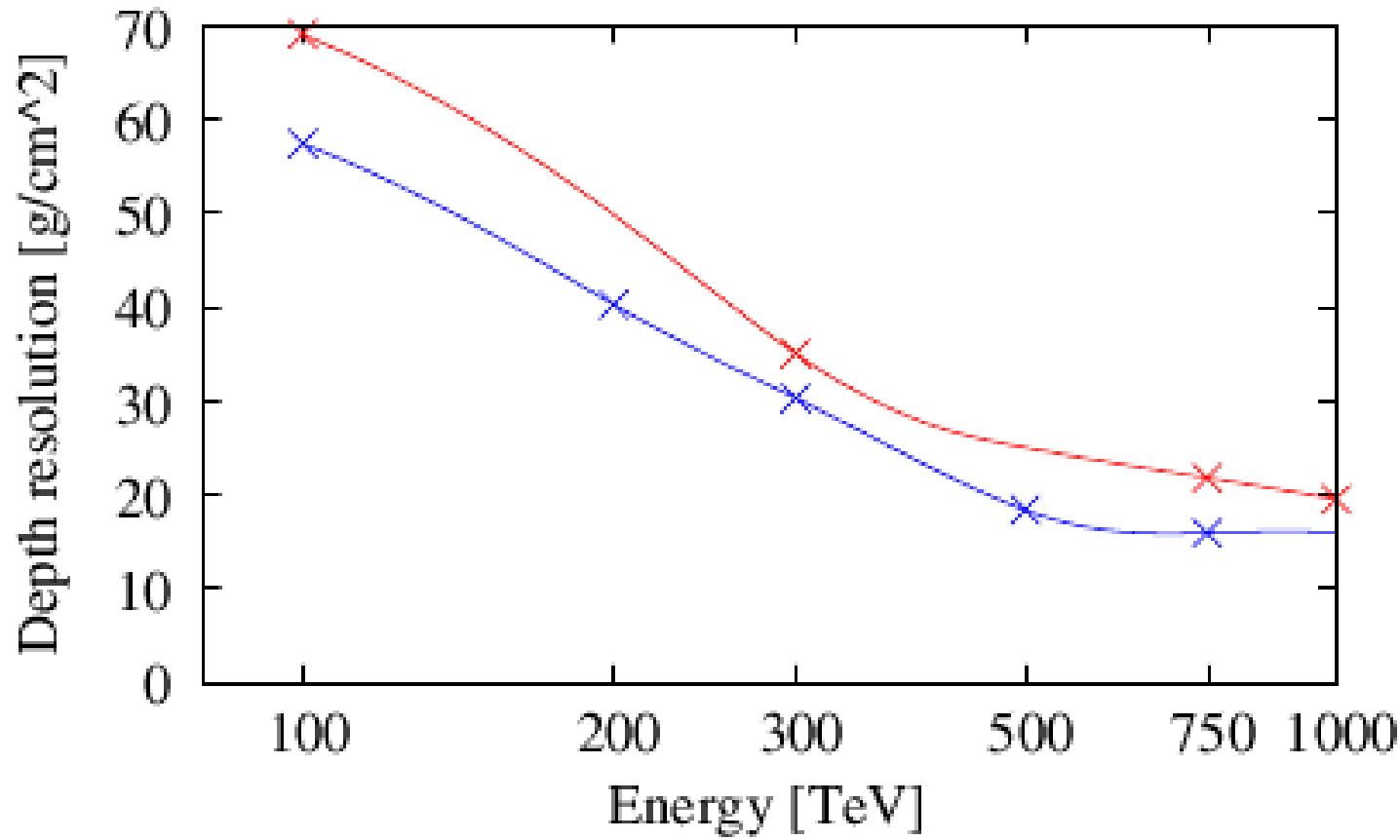
3) **Signal width:**
depth $\sim \langle w \rangle$

$$\langle w \rangle = \text{avg}[\text{width}(300\text{m}), \text{width}(400\text{m})]$$

4) **Signal peak:**
depth $\sim a$
(from time peak fit: $a x^2 + b$)



Shower Depth



Shower Depth & Gamma/Hadron Separation

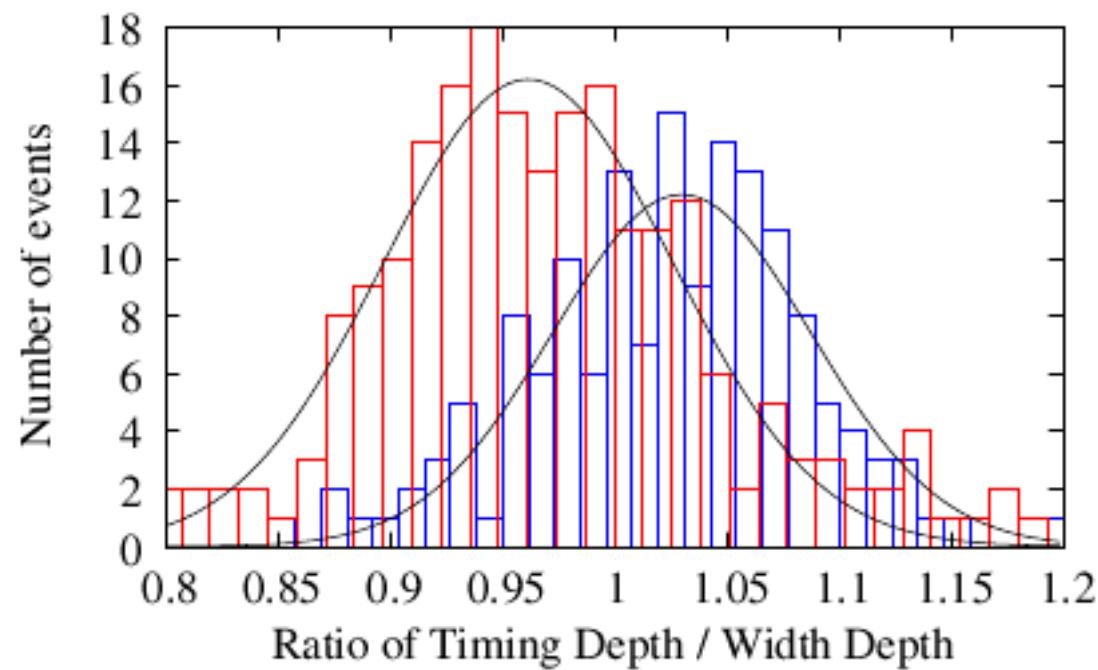
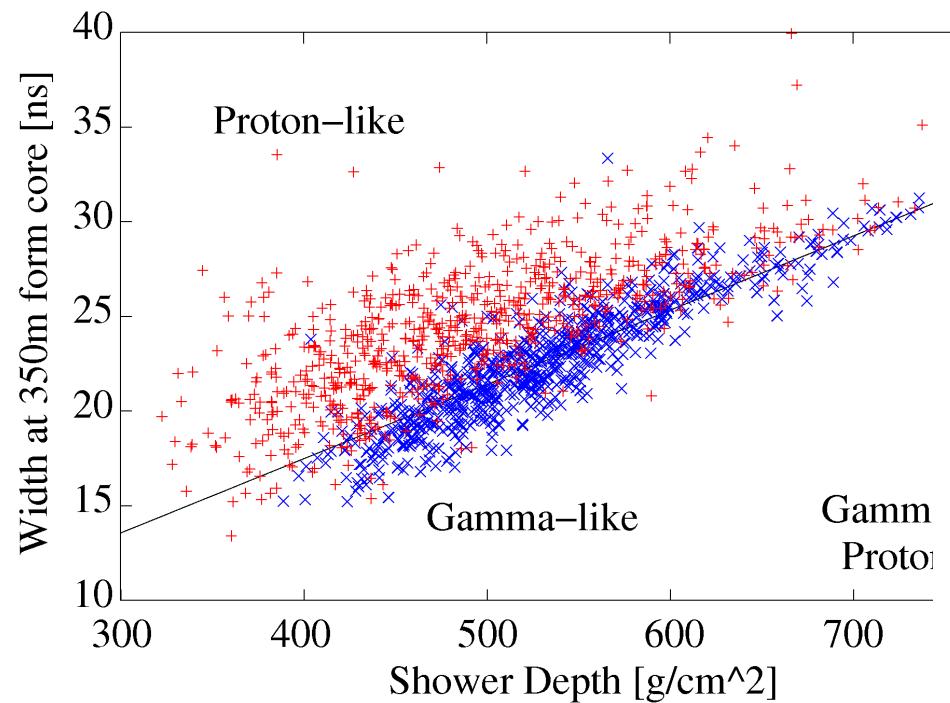
Differences in longitudinal shower development:

- **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: $D_{\text{peak}} / D_{\text{width}}$

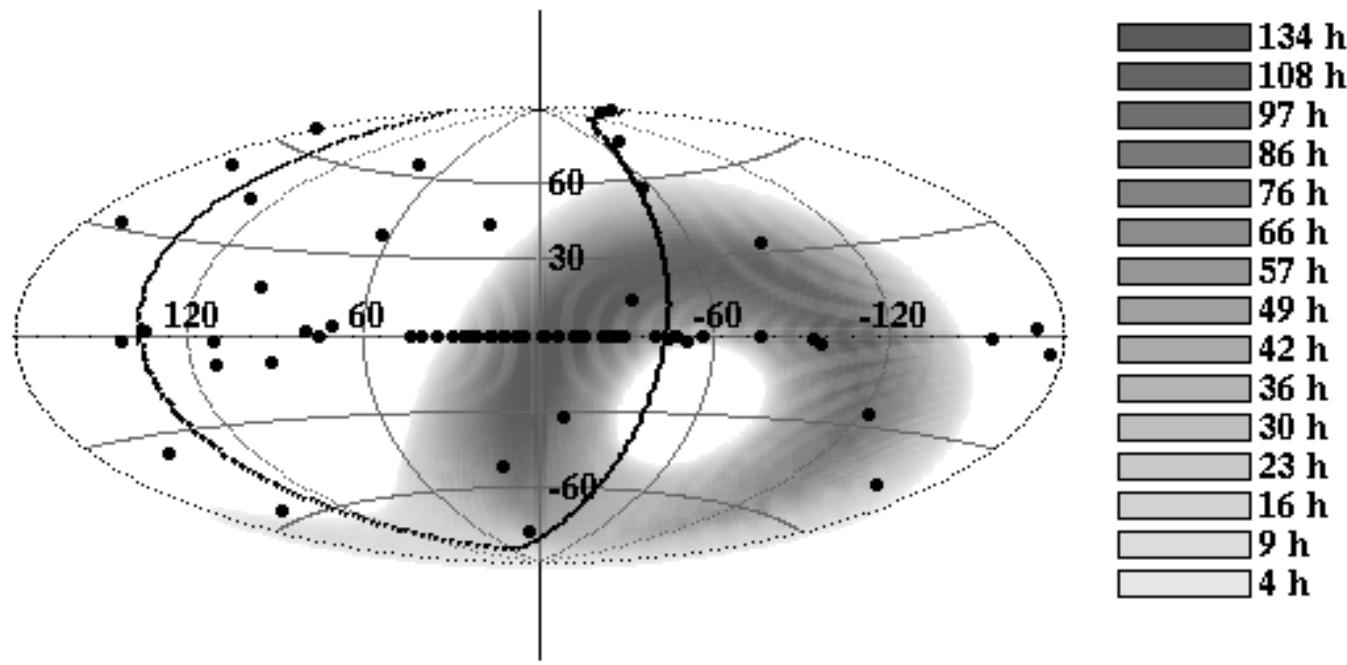


Flux Sensitivity

- Minimum point-source flux for which:
 5σ , >50 events, in 5 years (500 hours)
- Significance: $(\text{on-off}) / \sqrt{\text{on+off}} = N_g / \sqrt{N_g + 2 N_h}$
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

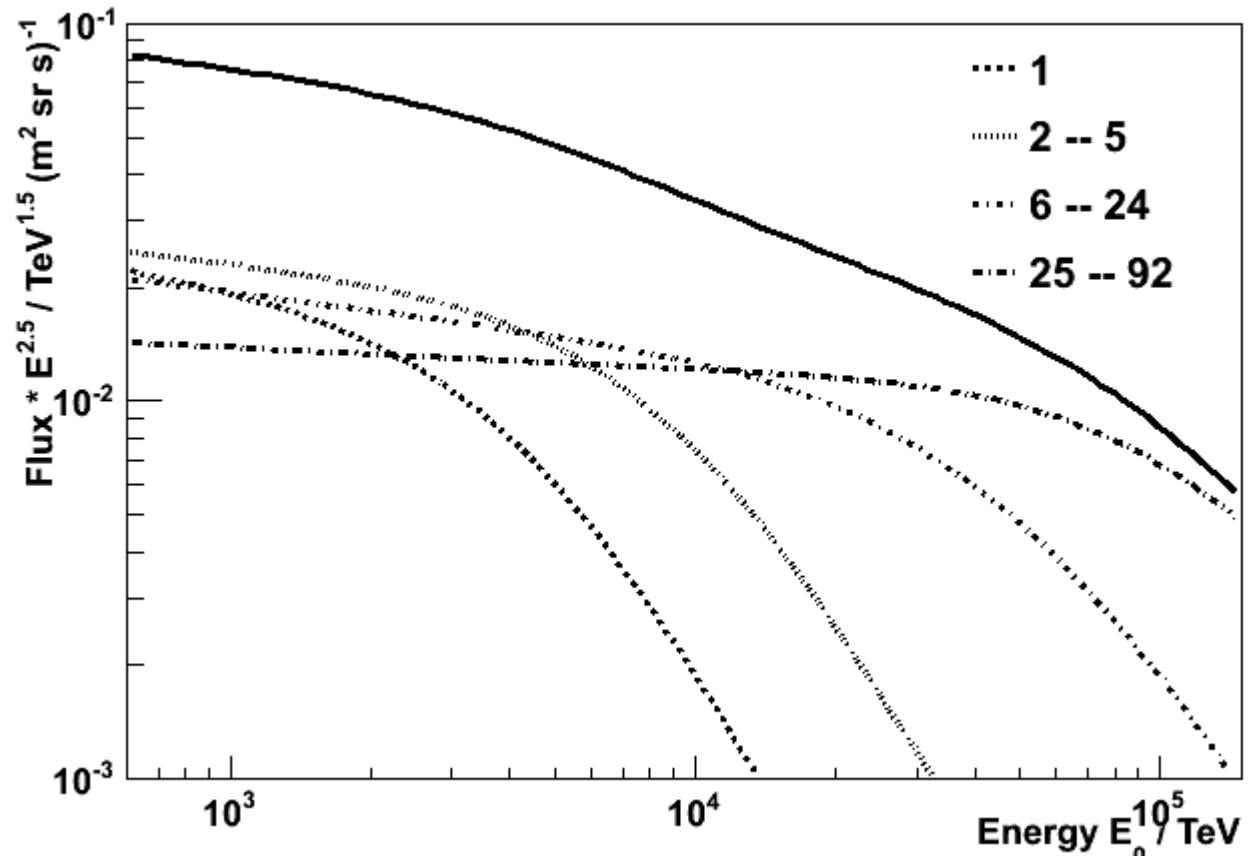
- Exposure time per year: 80 – 130 hours
- Tilt arrays after 5 years of operation:
 - *Tilted north field & tilted south deep field*



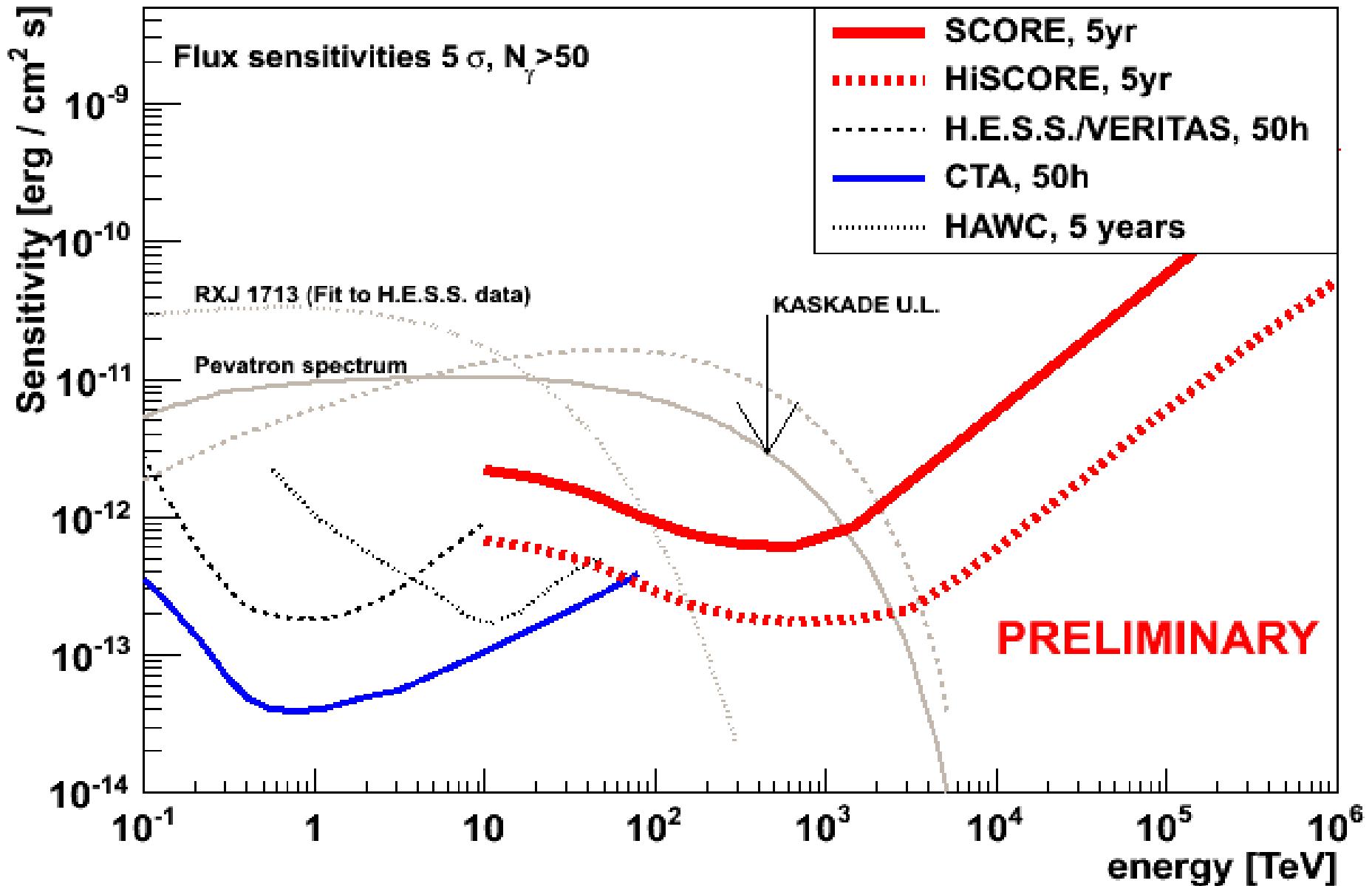
Daniel Hampf 2008

Hadrons

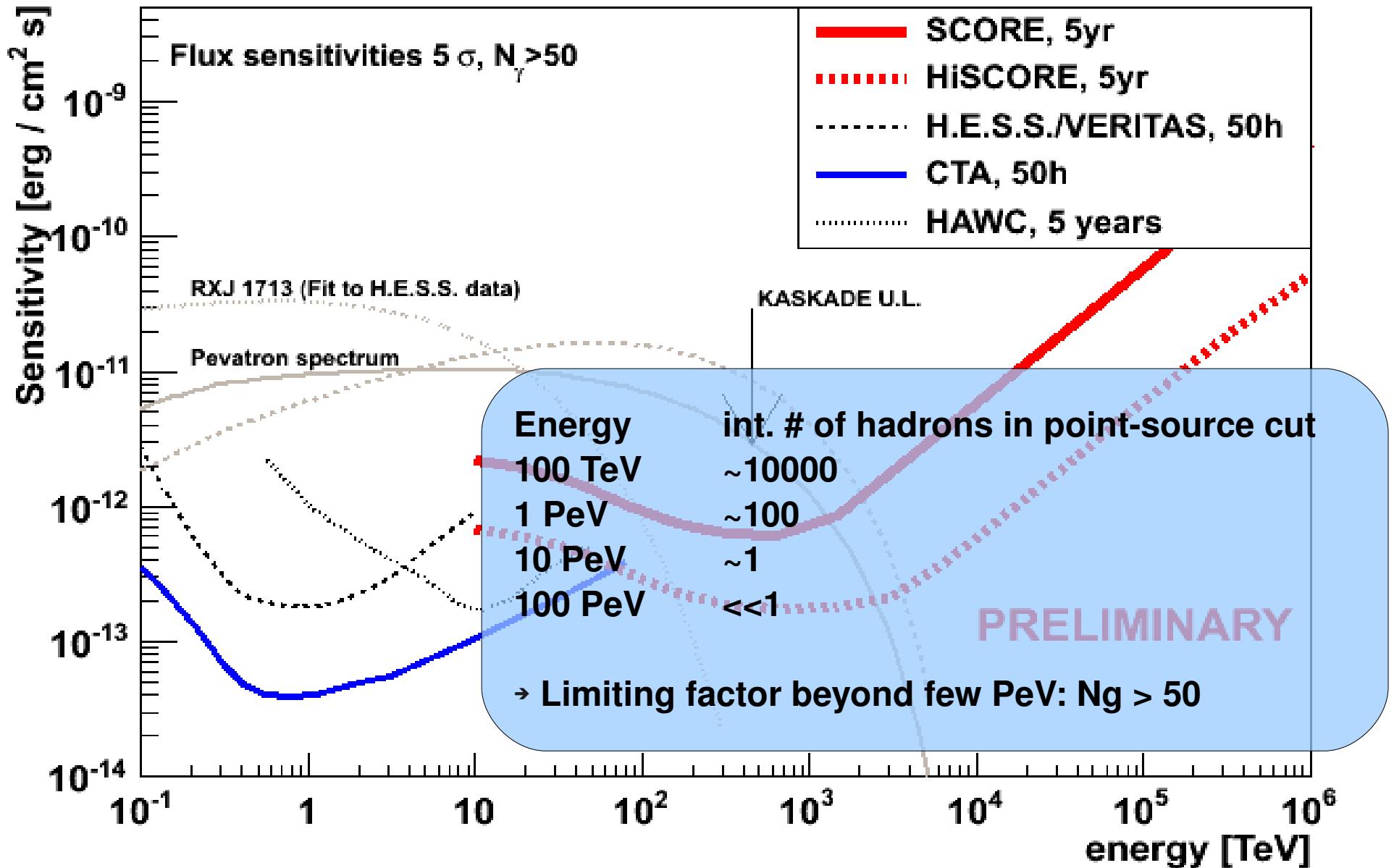
- Hoerandel 2003: polygonato model
- Hadron rates for SCORE, 10 m², 0.85 sr (theoretical rates):
 - E > 10 TeV: 25 kHz
 - **E > 100 TeV: 500 Hz**
 - E > 1 PeV: 10 Hz



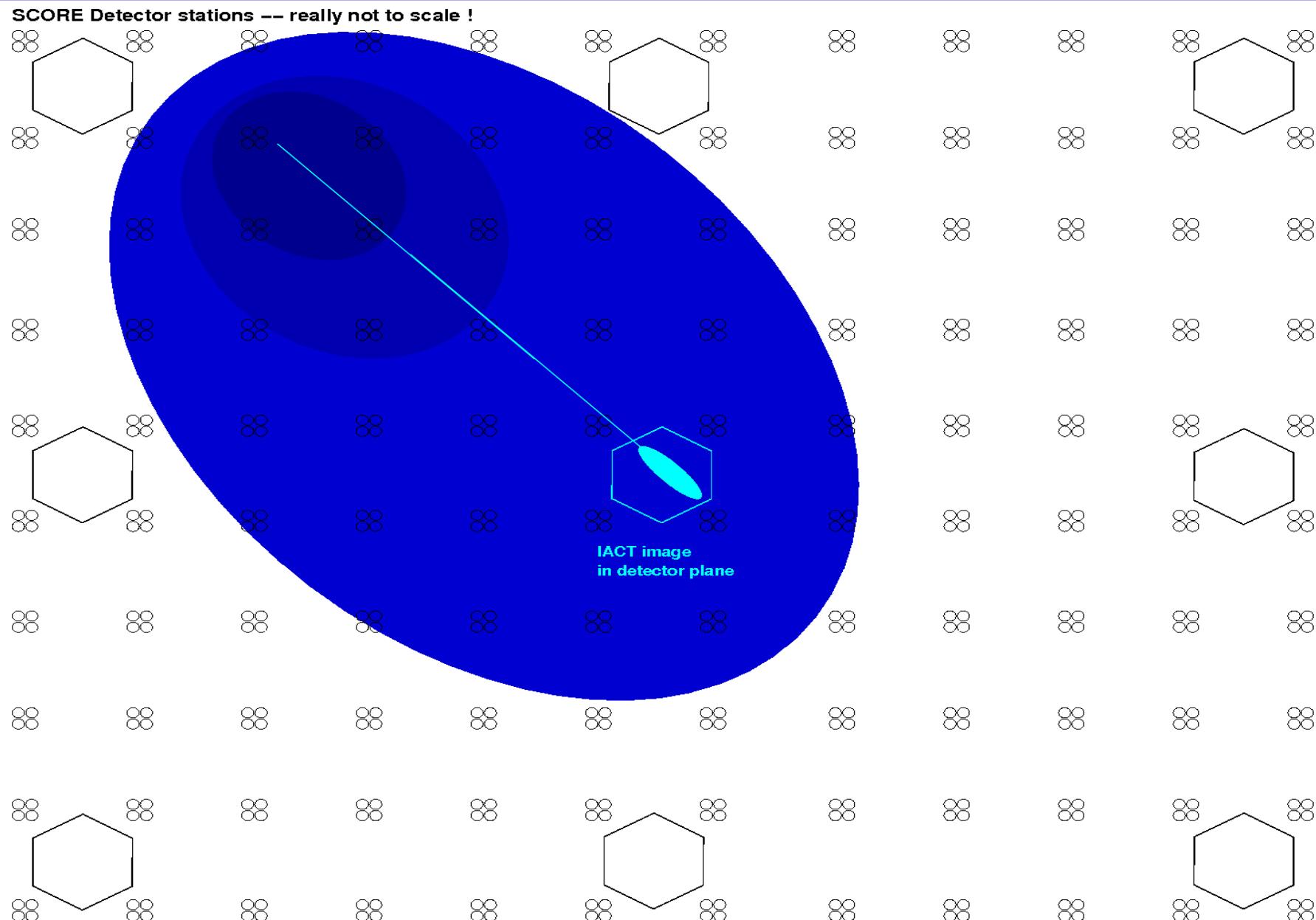
SCORE First Simulation Results



SCORE First Simulation Results



Combination with IACTs



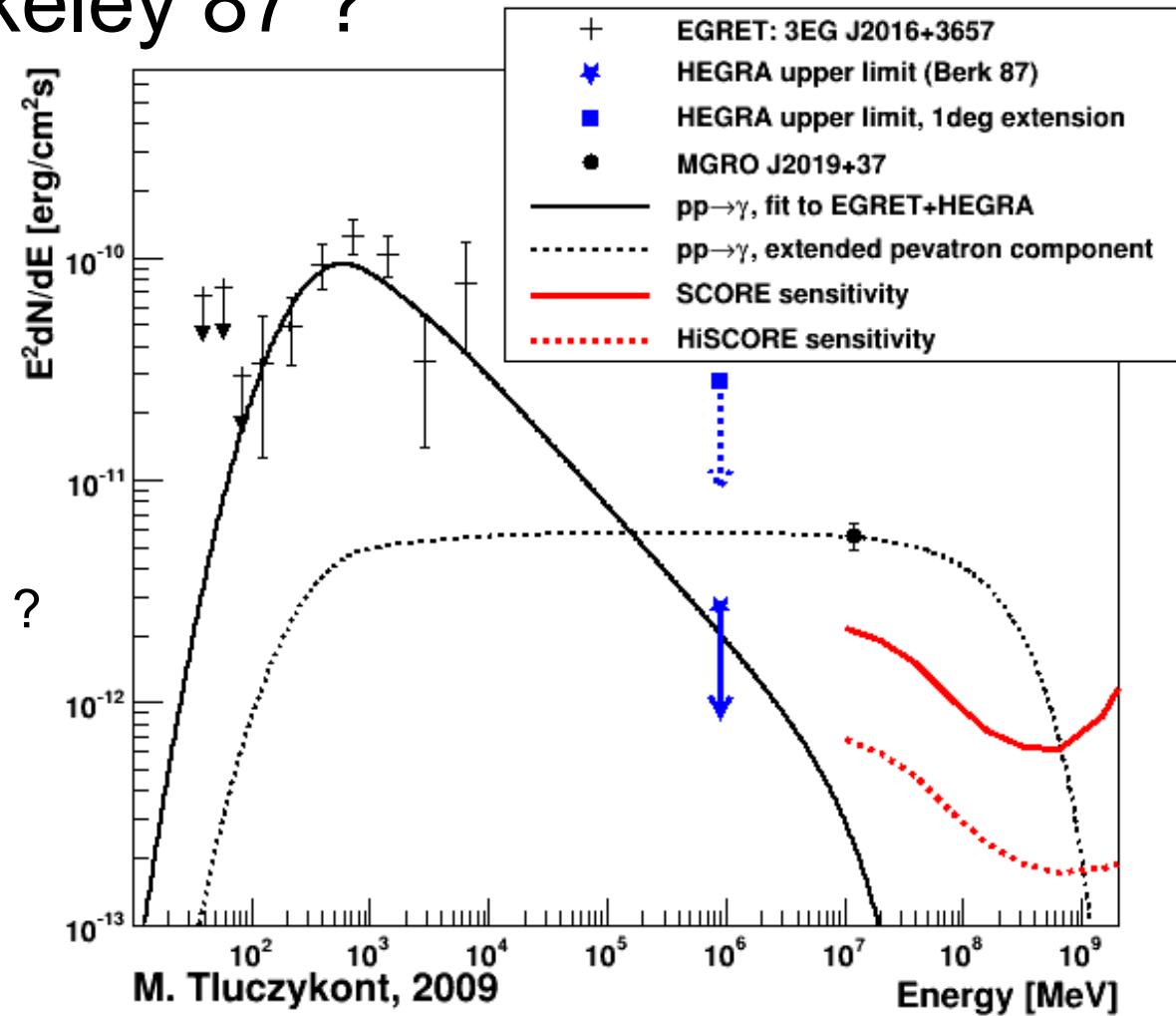
Combination with IACTs

- 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 Aeff / channel ratio !**
- Caveat: observations constrained to station viewcone (overcome this with station steering ...)
- Working on ... testing this in simulation

Pevatron emission from Cygnus ?

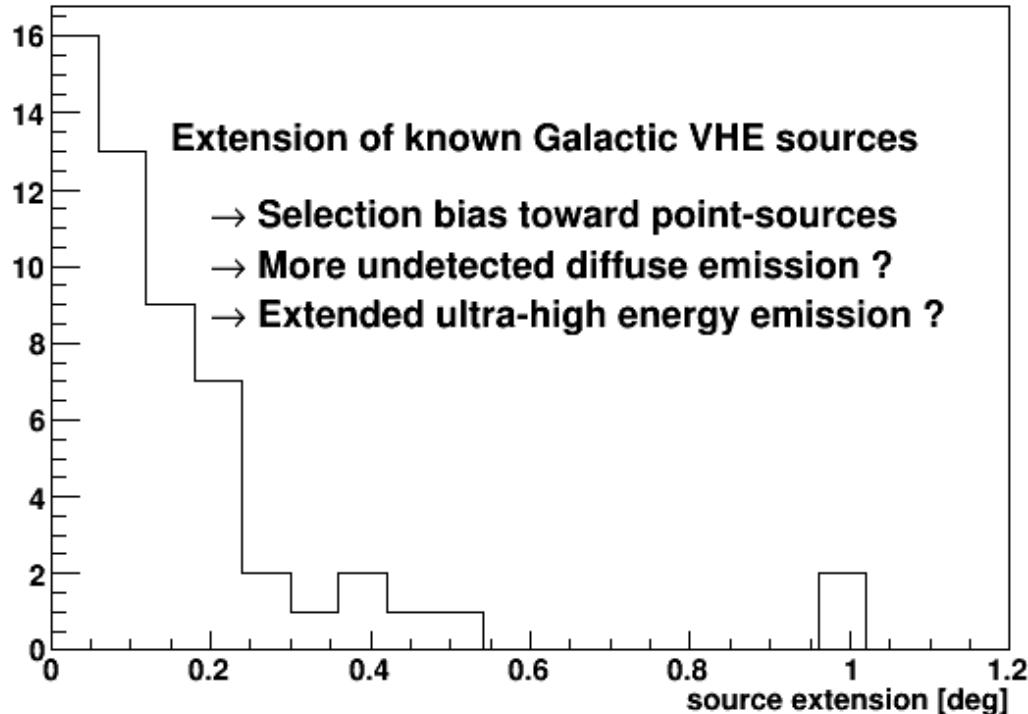
MGROJ2019+37 & Berkeley 87 ?

- 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**

Source Extension



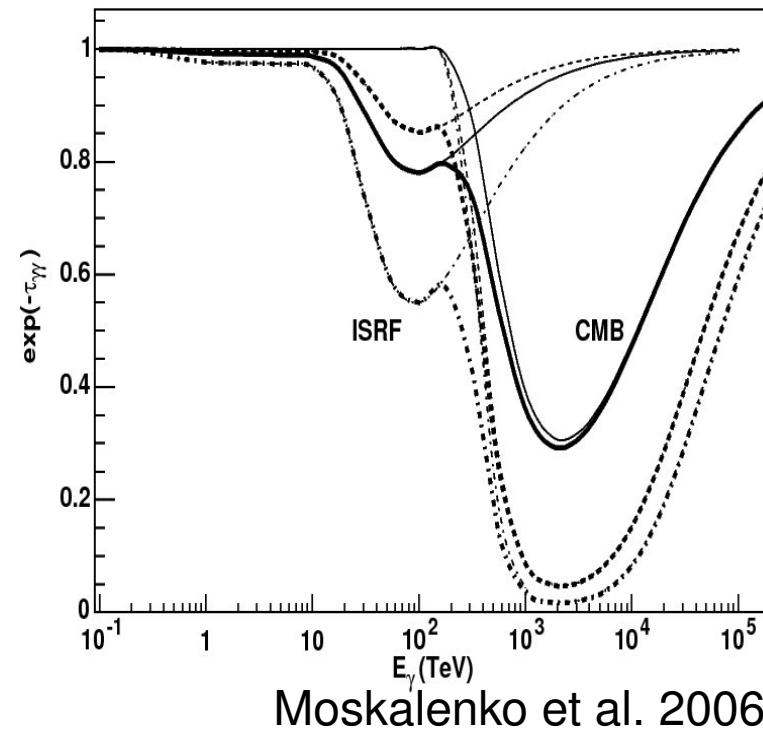
- Many Galactic objects are extended
- Extended emission: more background, less sensitivity
- Expect so far undetected extended sources !

The case of *pevatrons*

- Acceleration up / beyond knee = 3 PeV
- Need long acceleration time / large scales
- Extended pevatron emission ?

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)



Moskalenko et al. 2006

Local Supercluster and UHECRs

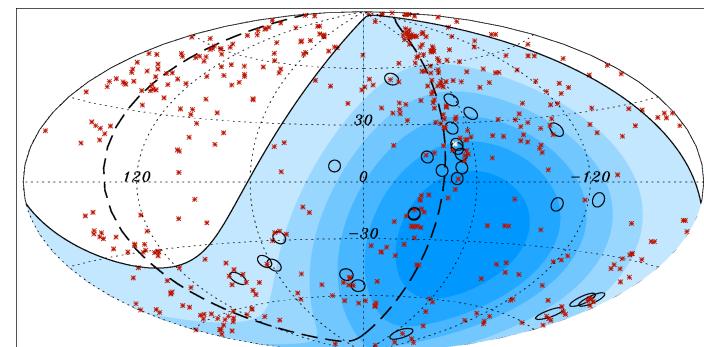
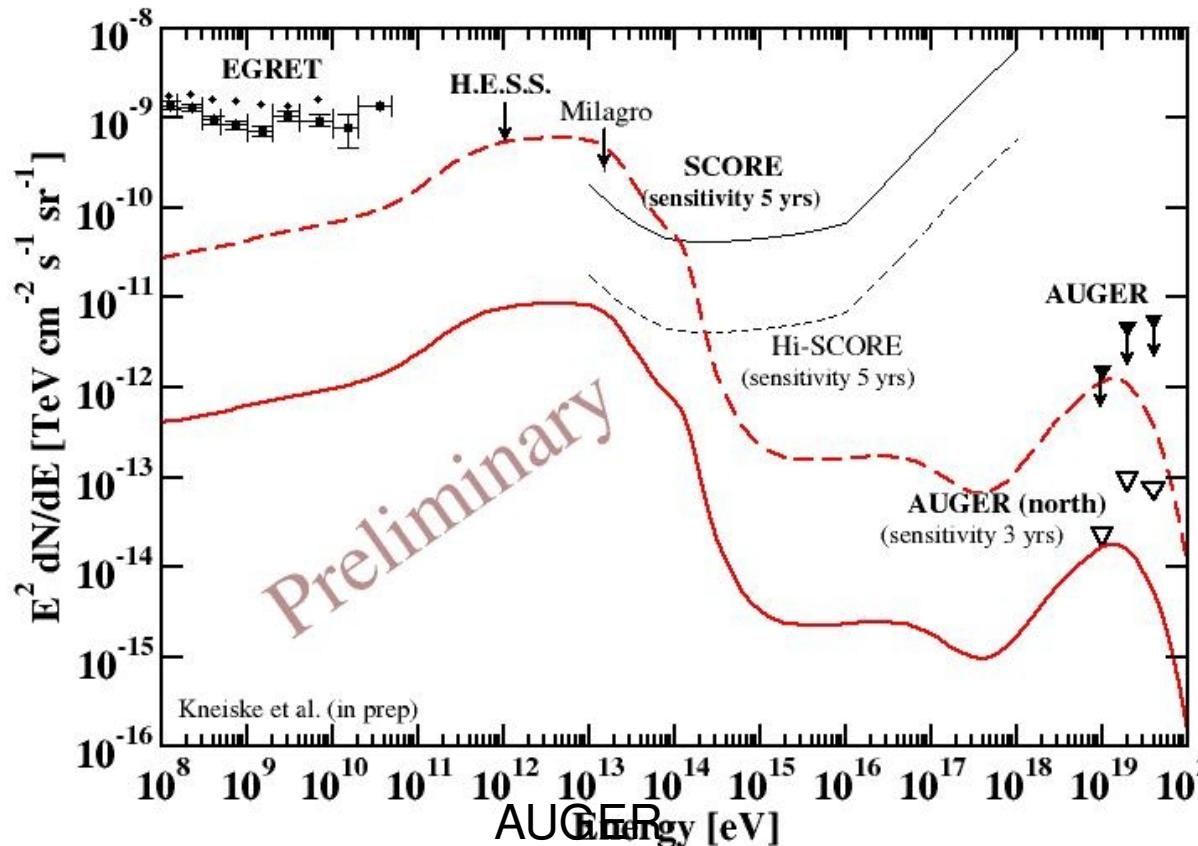
- UHECRs

confined in **local supercluster**

Expect diffuse emission

See *T. Kneiske, Lodz 2009*

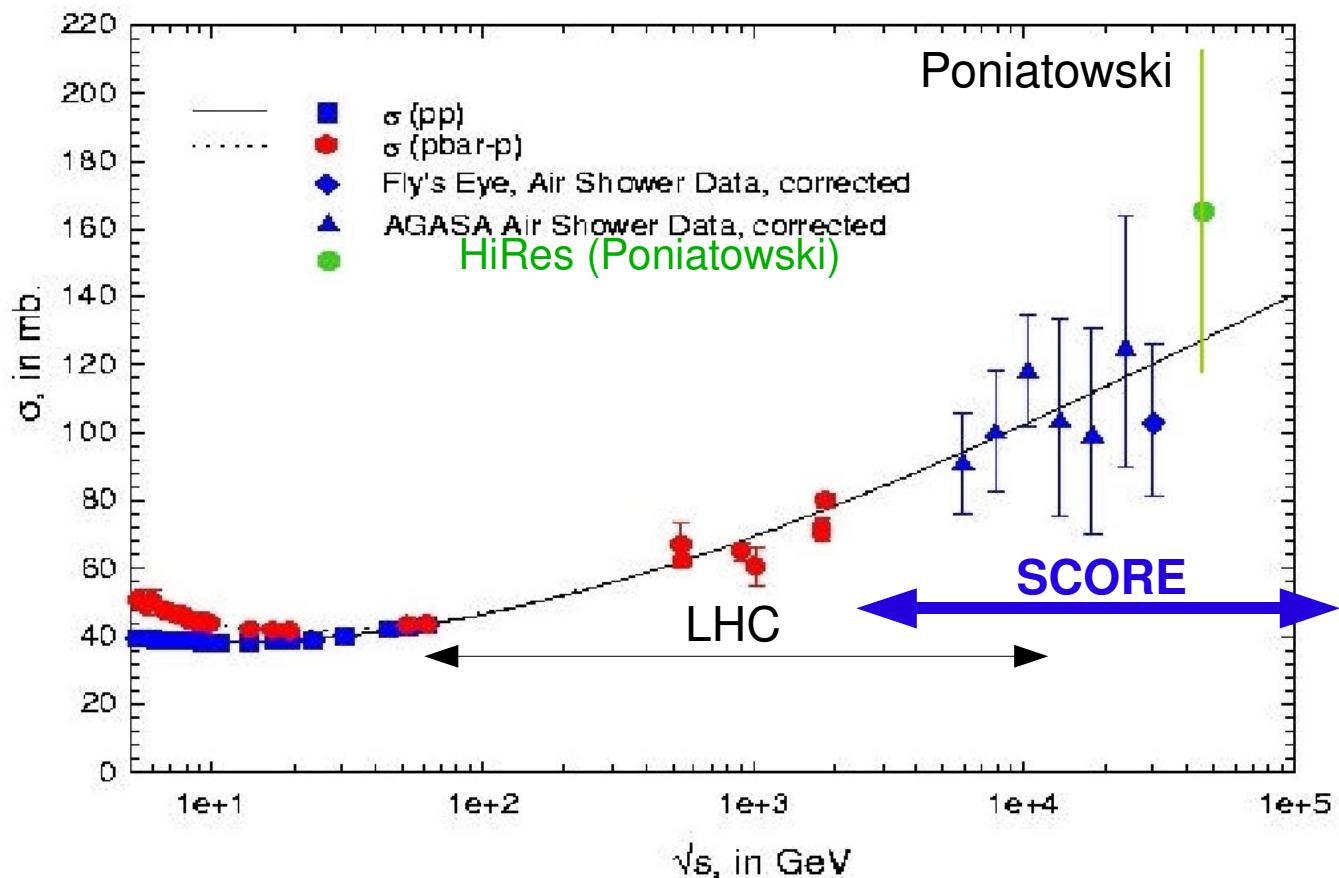
- Point-sources from AGN ?
 - IC Pair-cascading
 - Haloes ?



p-p cross-section

- Correlation shower depth / first interaction
→ measure interaction length in air $\sigma(p\text{-}p)$
- SCORE: $1 < E_{\text{CM}} < 150 \text{ TeV}$

- Overlap: LHC,
CR experiments



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 ?

Summary

- **Many physics cases beyond 10 TeV primary energy**
 - Gamma-ray astronomy (Origin of cosmic rays, ...)
 - Cosmic-ray physics
 - Particle physics
- **SCORE**
 - Opens the last remaining Gamma-ray observation window
 - Spans sub-knee to pre-ankle CR-energy range

Outlook

- We invite for collaboration !
- **H_iSCORE**
Hundred Square-km Cosmic ORigin Explorer
- Extension / Synergies with other techniques
 - Radio (LOFAR)
 - Szintillation counters (hybrid array)
 - Possible combination with imaging Cherenkov technique

Status

- Full detector simulation complete
 - Testing different layouts
 - Optimizing reconstruction
 - Studying combination with IACTs
- Studies of first Hardware components in progress
- Construction of first prototype station in progress
- Funding for first SCORE stage pending
- Collaboration with other institutes is welcome !

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 ?
- ...

Amplitude: The Lateral Density Function

Number of photons

1e+06

100000

10000

1000

100

100 200 300 400 500 600 700 800 900 1000

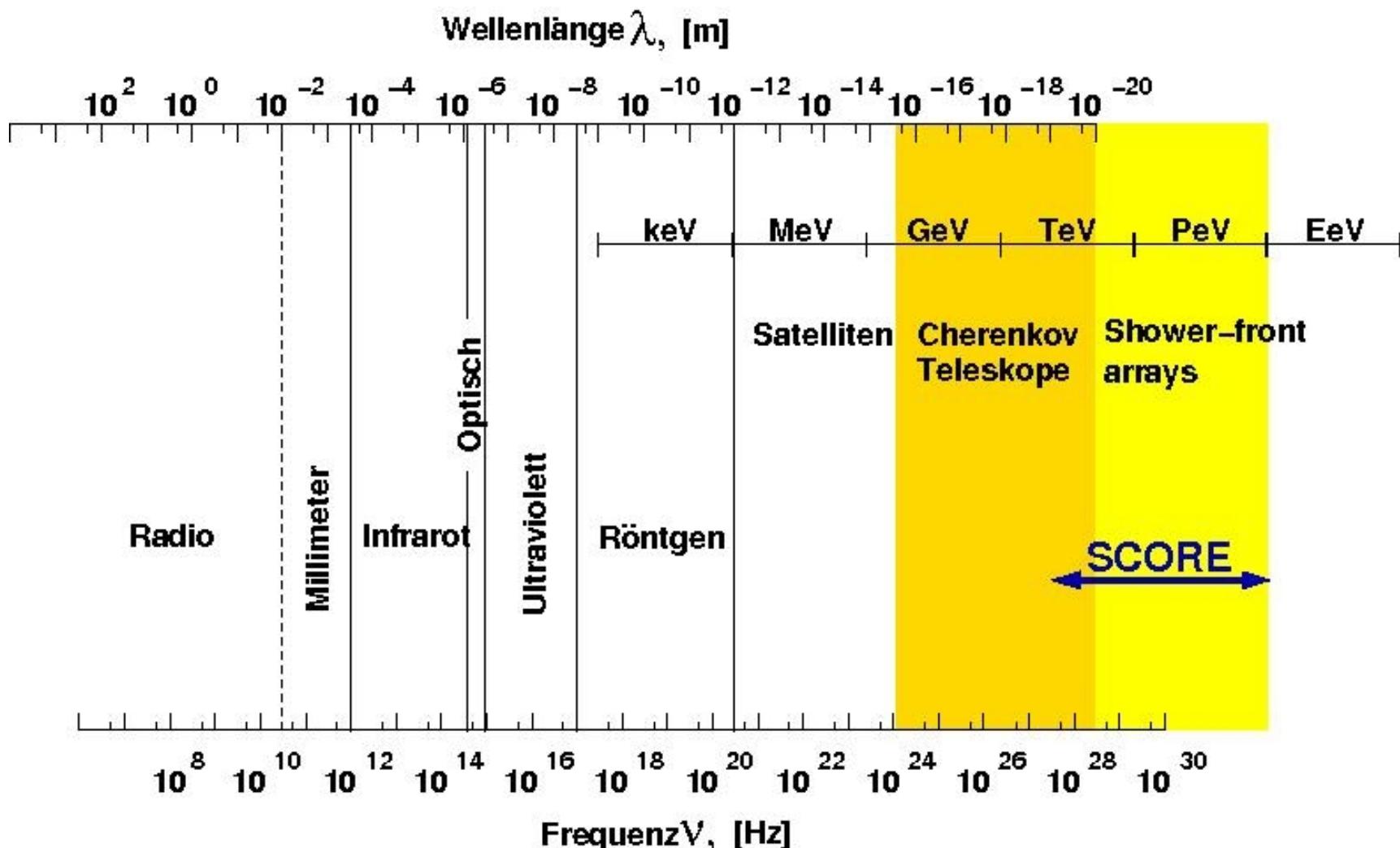
Distance from Shower Core [m]

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

WITHOUT NOISE !

- 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

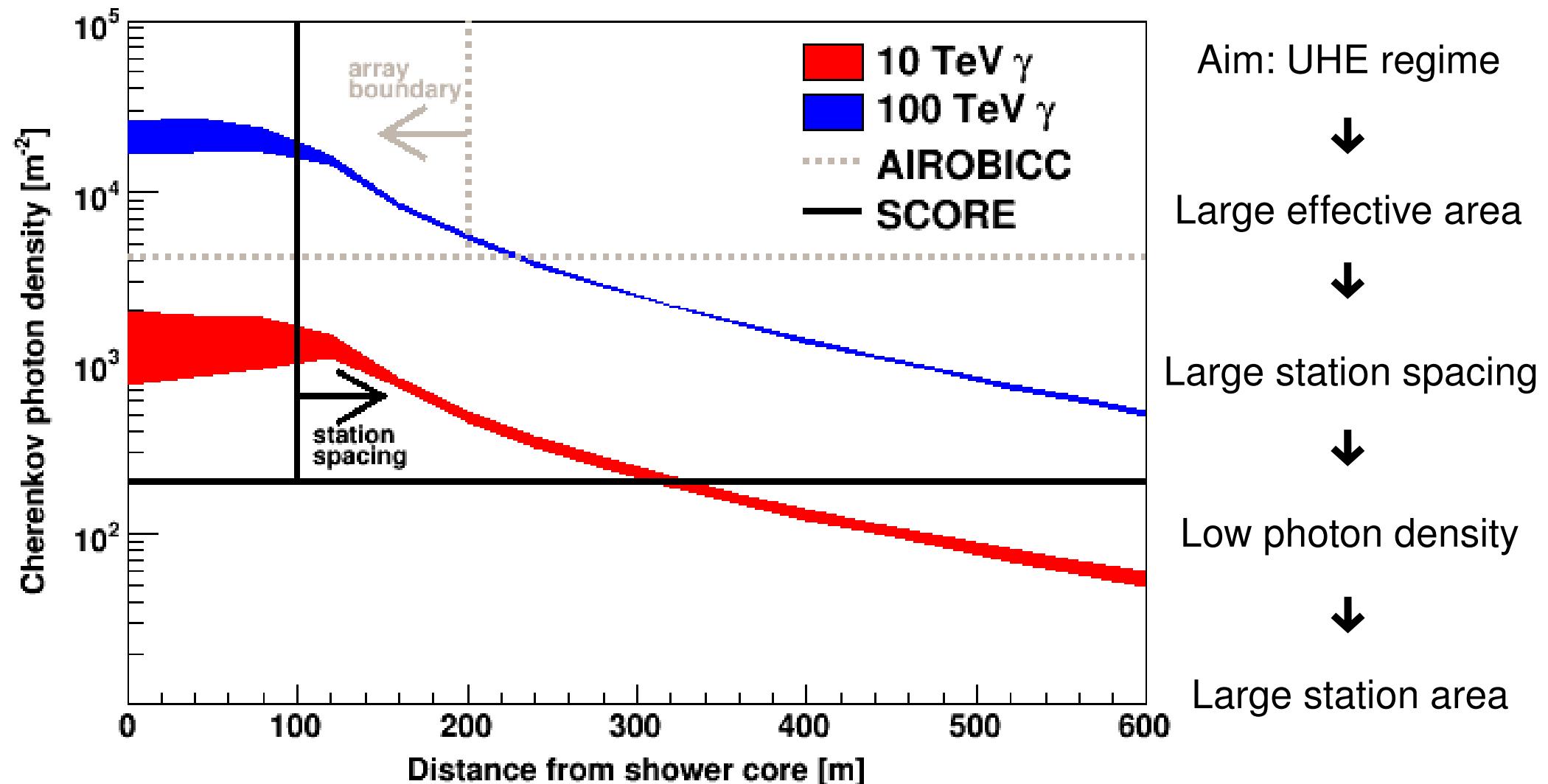
Challenges

- Gamma-hadron separation
- Night-Sky Background suppression

Benefits

- High photon-statistics per shower
- Channel-per-km² factor
 - IACTs: ~25000
 - SCORE: < 200
- **Lateral photon density distribution ...**

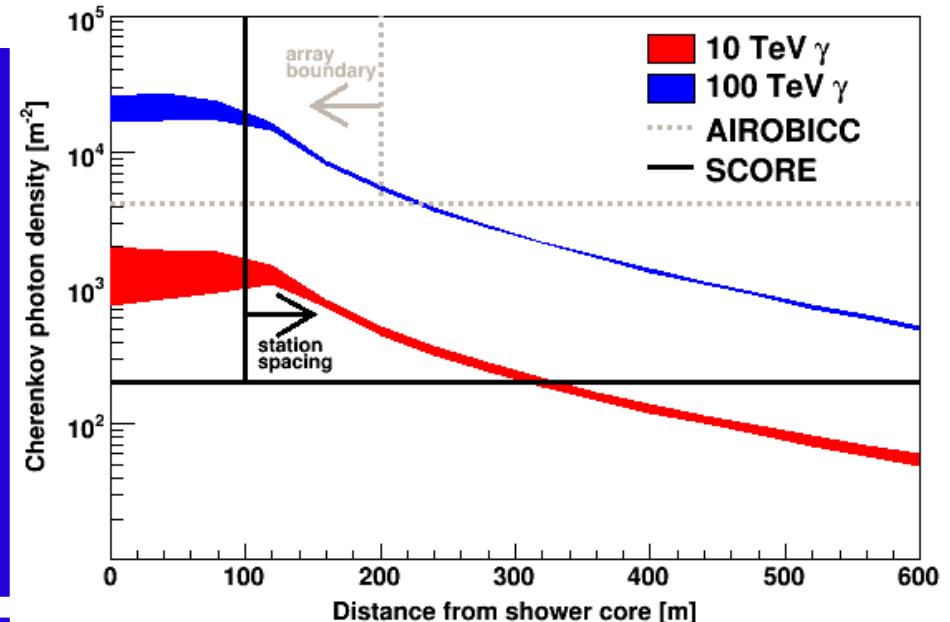
The SCORE Detector



Cherenkov Technique

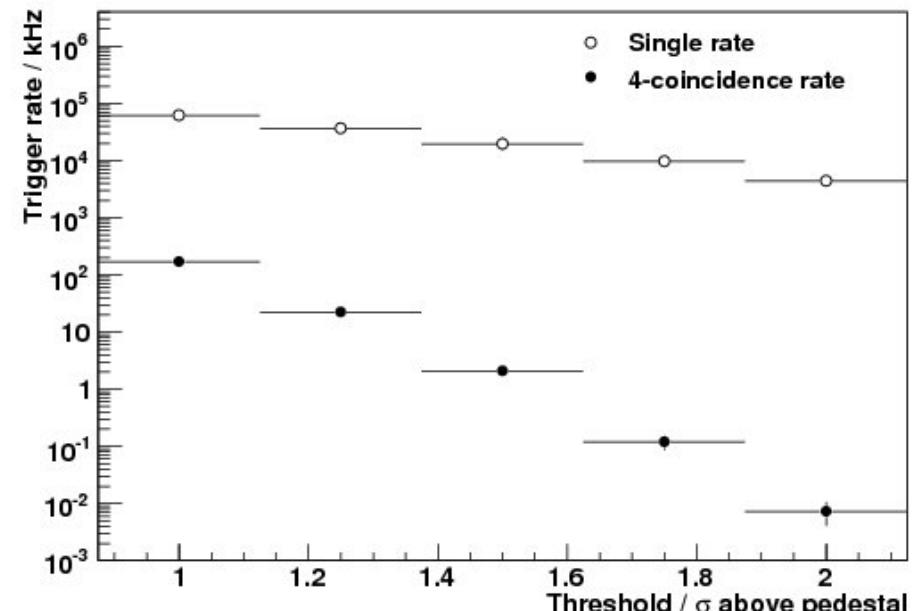
Benefits

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



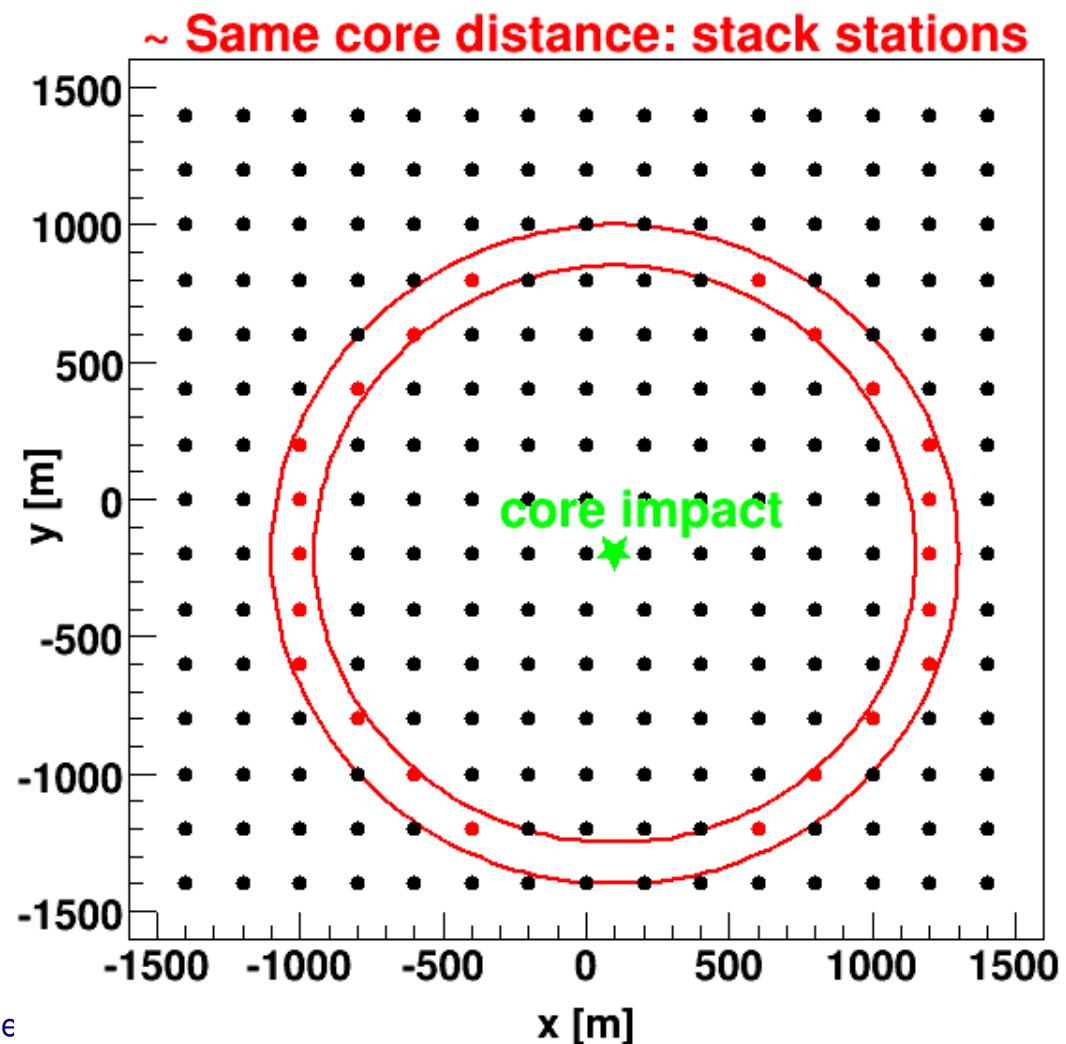
Limiting factors

- Channel-per-km²
 - IACTs: ~ 25000 (imaging)
 - SCORE: < 200 ! (non-imaging)
- Night-Sky-Background



Station Stacking

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



Shower-front sampling arrays

	SCORE	HiSCORE	TUNKA	BLANCA	AIROBICC
instrumented area [km ²]	10	100	1	0.2	0.04
detector station area [m ²]	~0.5	~0.5	0.12	0.1	0.13
field of view [sterad]	0.84	0.84	1.8	0.12	1
station spacing [m]	200	200	85	35	30
# of channels	<1000	<10000	133	144	49