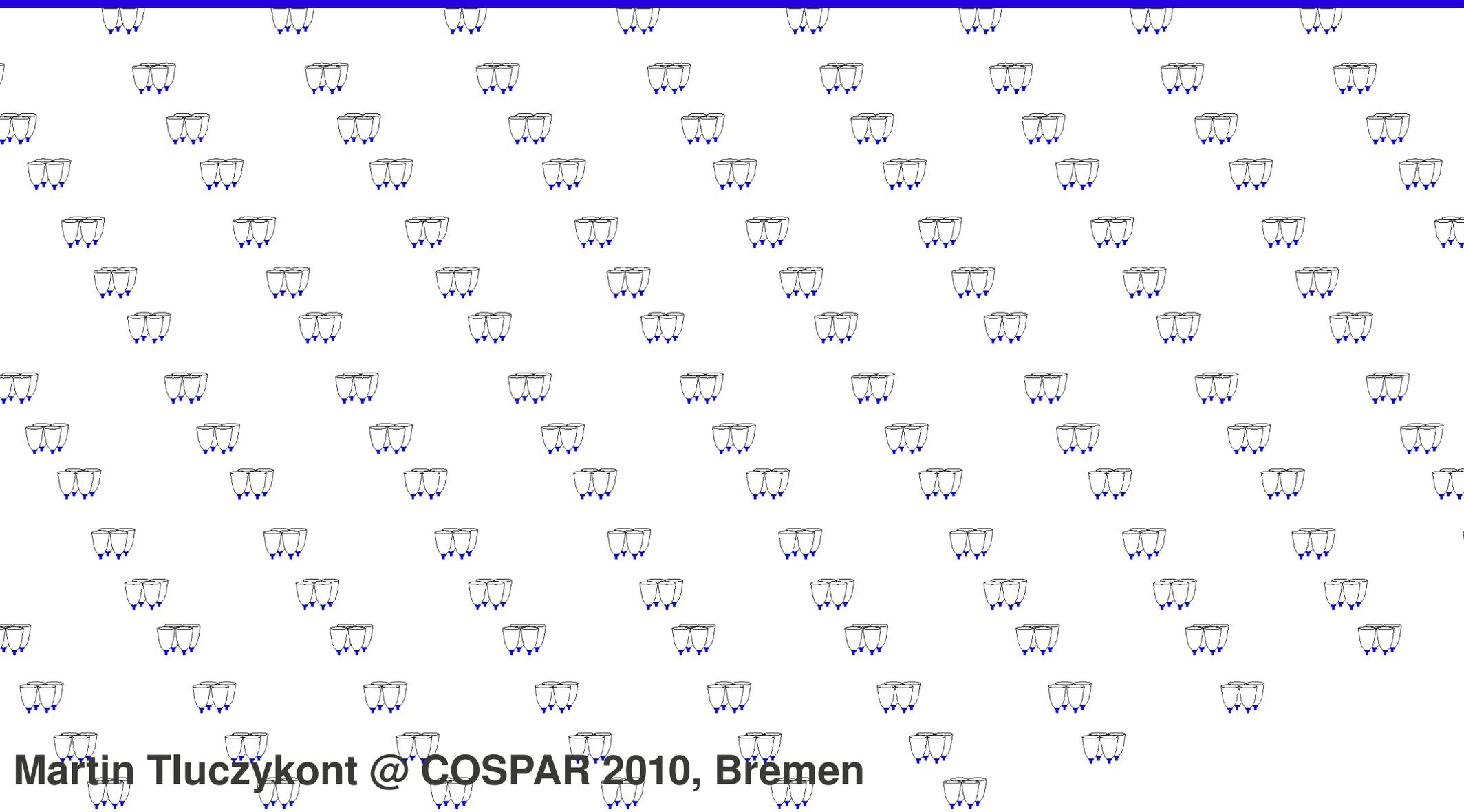


The ground-based wide-angle gamma-ray and cosmic-ray experiment

HiSCORE



Martin Tluczykont @ COSPAR 2010, Bremen

The ground-based wide-angle gamma-ray and cosmic-ray experiment HiSCORE

Martin Tluczykont, Daniel Hampf, Dieter Horns, Tanja Kneiske,
Robert Eichler, Rayk Nachtigall

Universität Hamburg, department of physics, Luruper Chaussee 149, 22761 Hamburg

Gavin Rowell

University of Adelaide 5005, School of Chemistry & Physics, Australia

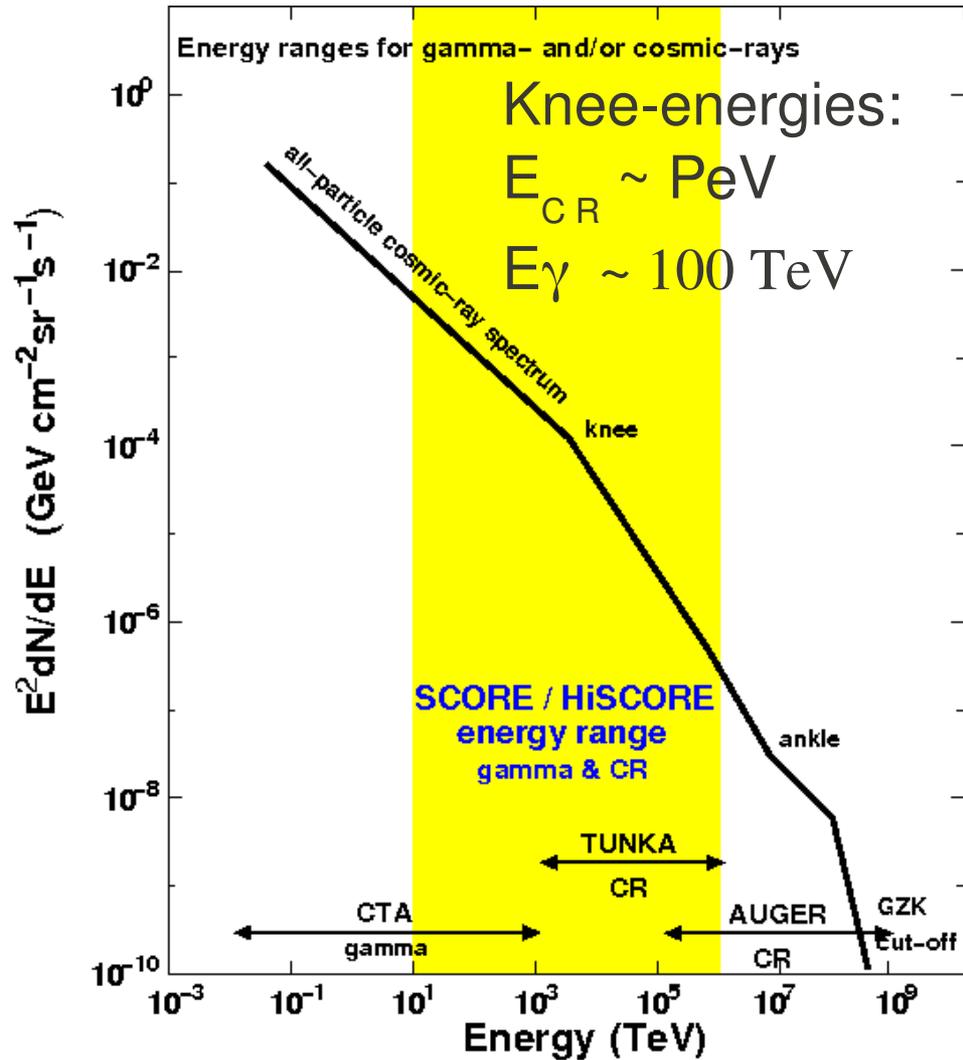
Physics motivations

Principle of the array

Status & outlook



SCORE / HiSCORE aims



Cosmic-rays:

$$100 \text{ TeV} < E_{CR} < 1 \text{ EeV}$$

Gamma-rays:

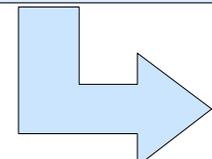
$$E_{\gamma} > 10 \text{ TeV}$$

Large area: 10-100 km²

Large Field of view: $\sim 0.6 \text{ sr}$

Roadmap phase I recommends:

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



We propose HiSCORE !

SCORE = Study for a Cosmic ORigin Explorer $\sim 10 \text{ km}^2$

HiSCORE = Hundredi* Square-km Cosmic ORigin Explorer $\sim 100+ \text{ km}^2$**

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

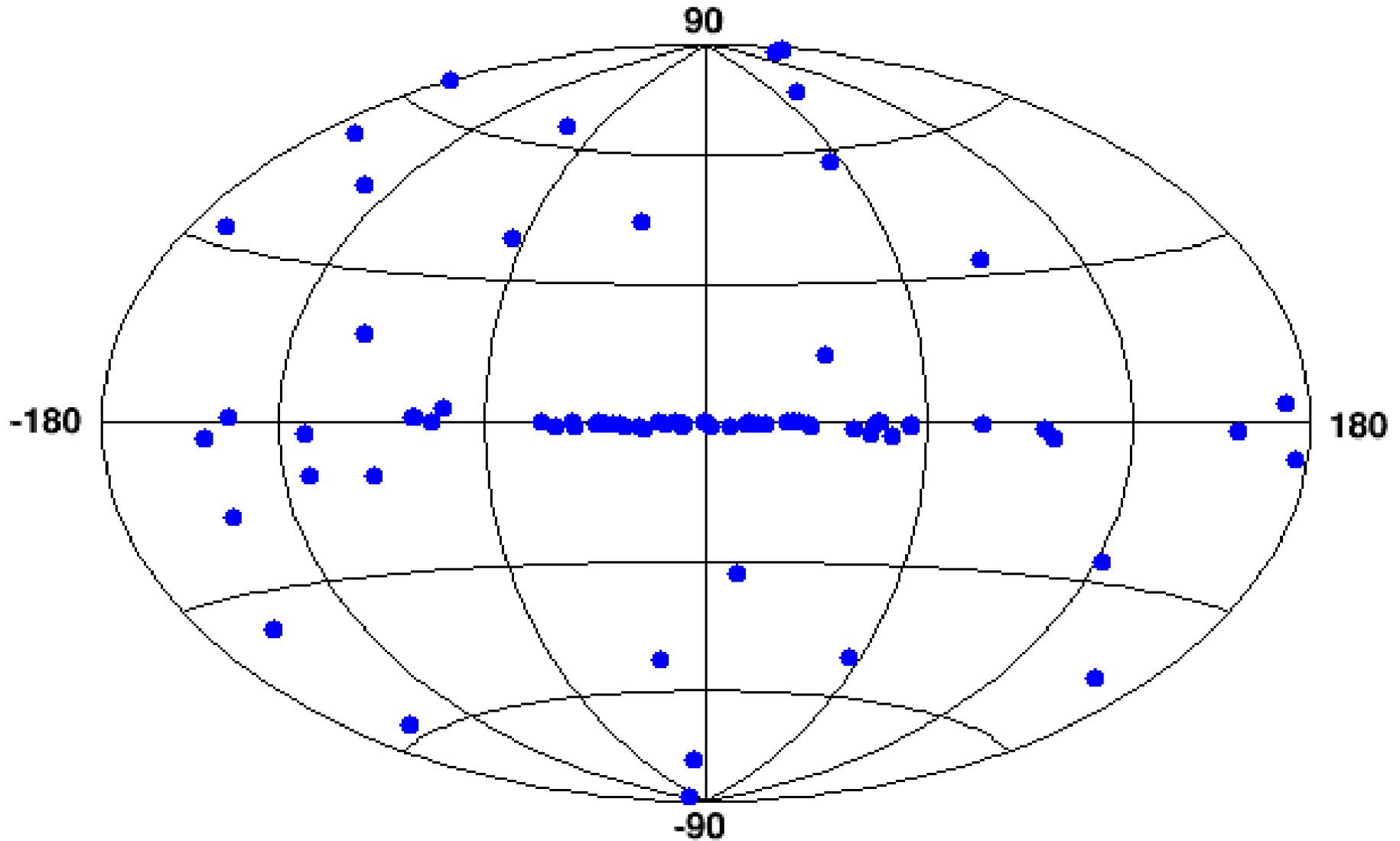
Composition / anisotropies
Sub-knee to pre-ankle

Particle physics beyond LHC

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

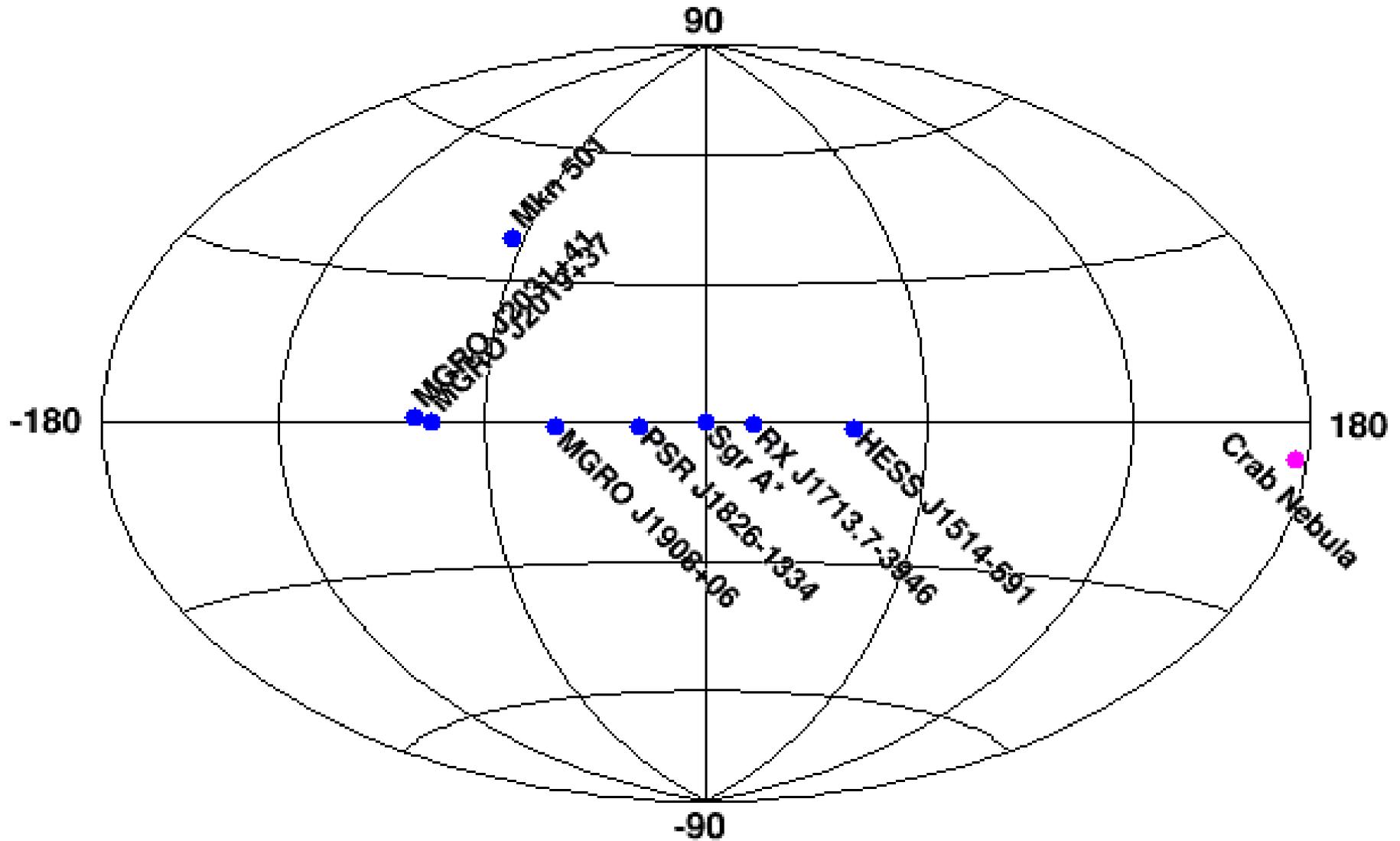
Gamma-Ray Sky, $E > 100\text{GeV}$

VHE gamma-ray sky 2009



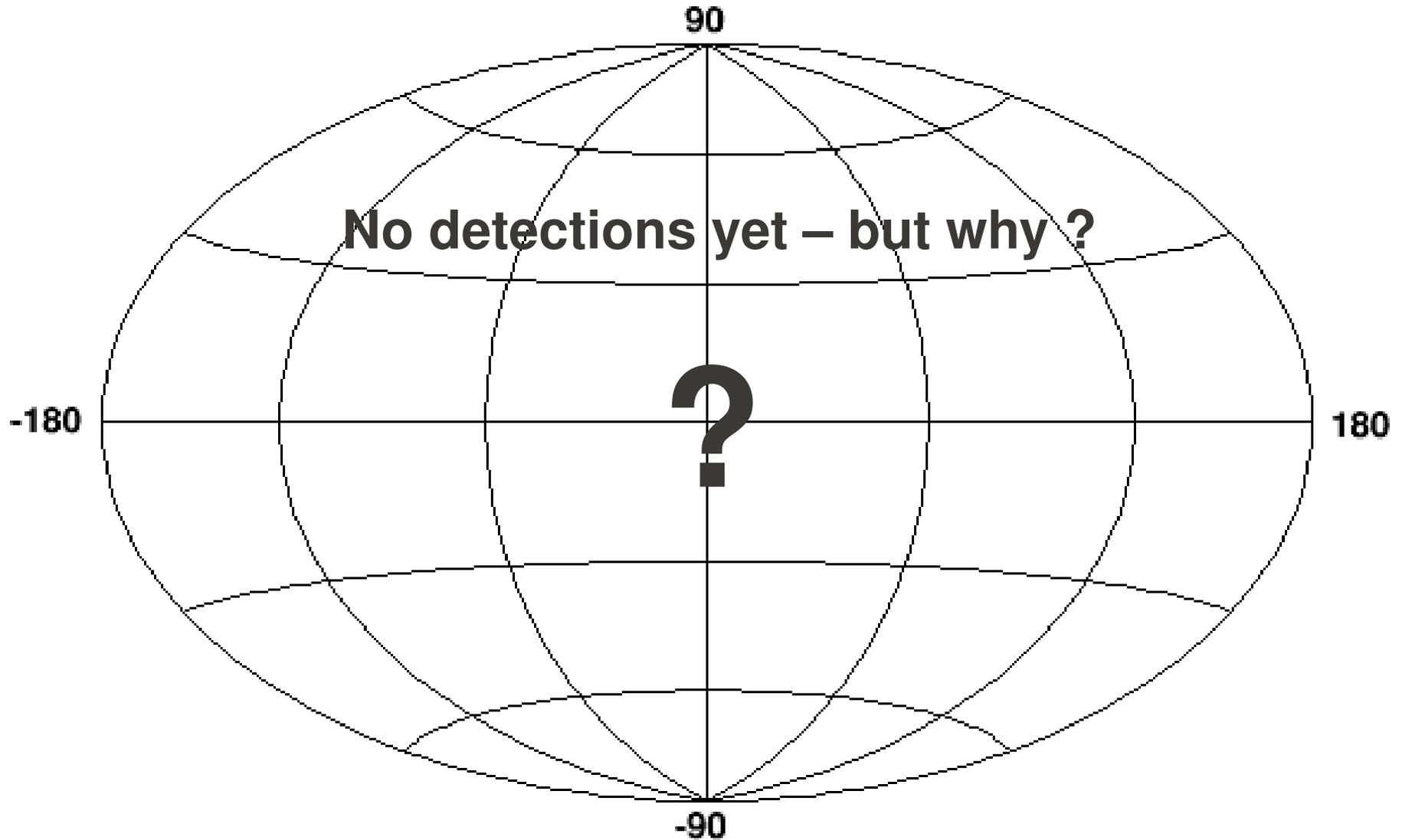
Gamma-Ray Sky, $E > 10 \text{ TeV}$

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

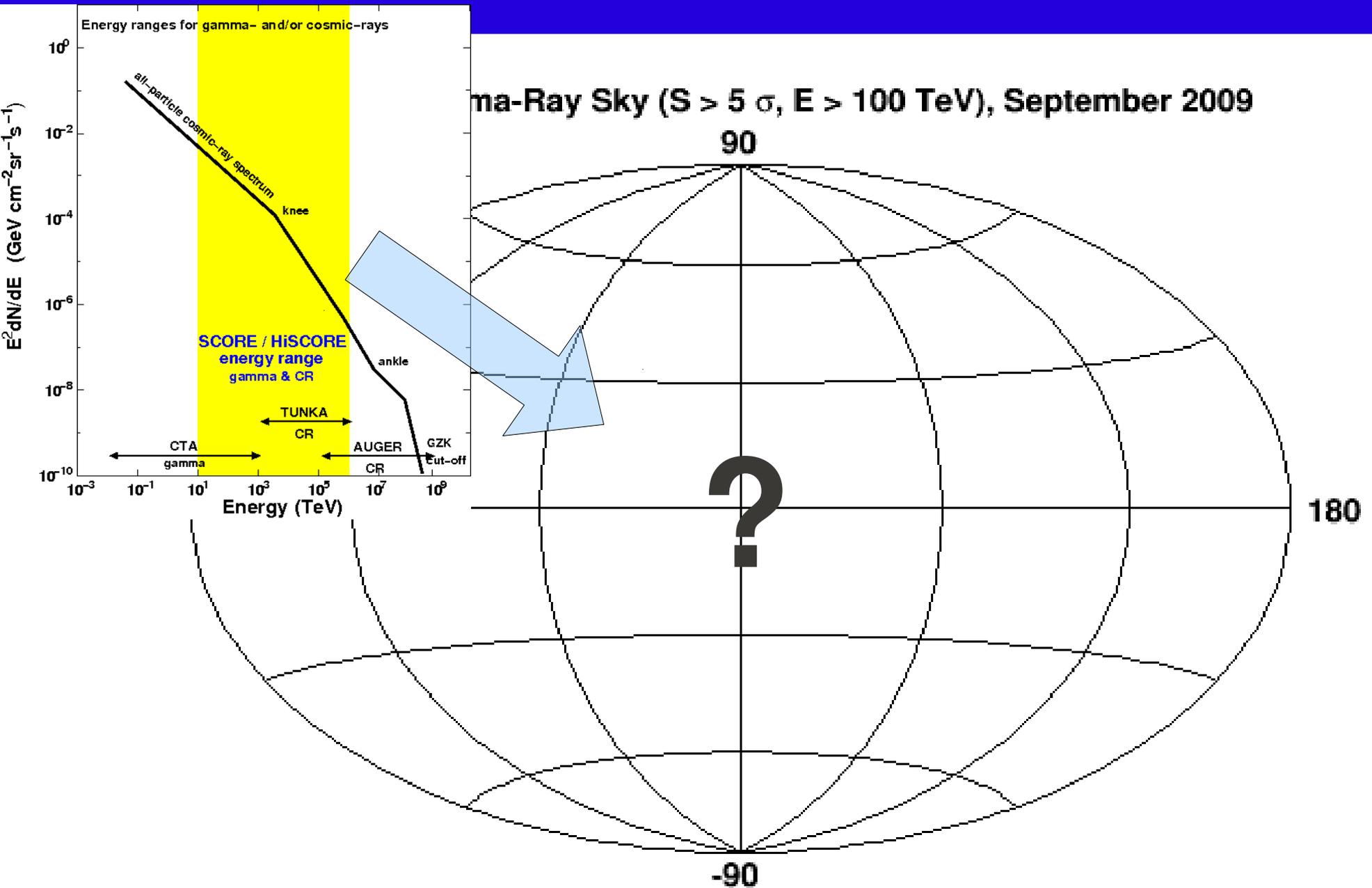


Gamma-Ray Sky, $E > 100 \text{ TeV}$

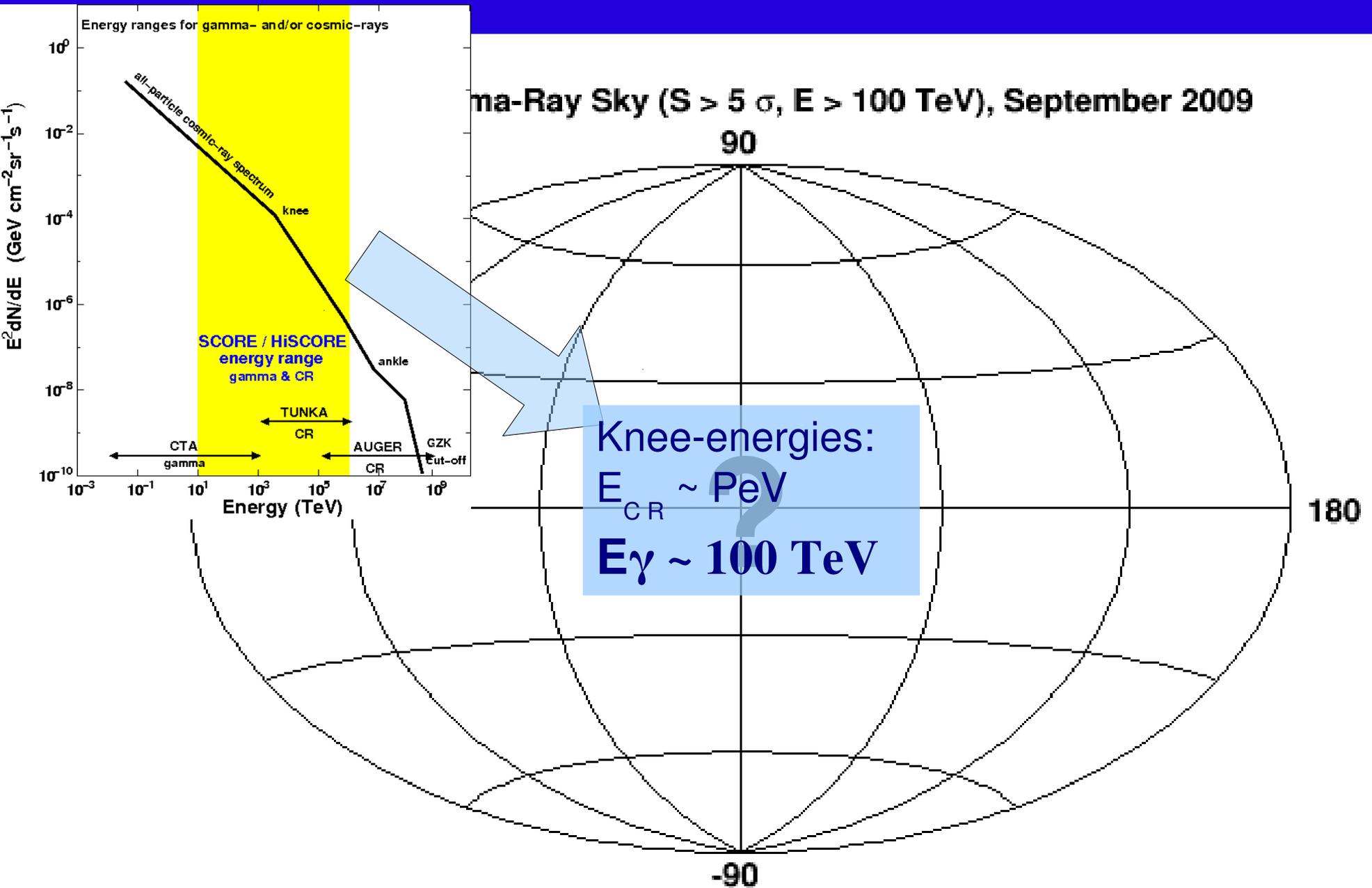
UHE Gamma-Ray Sky ($S > 5 \sigma$, $E > 100 \text{ TeV}$), September 2009



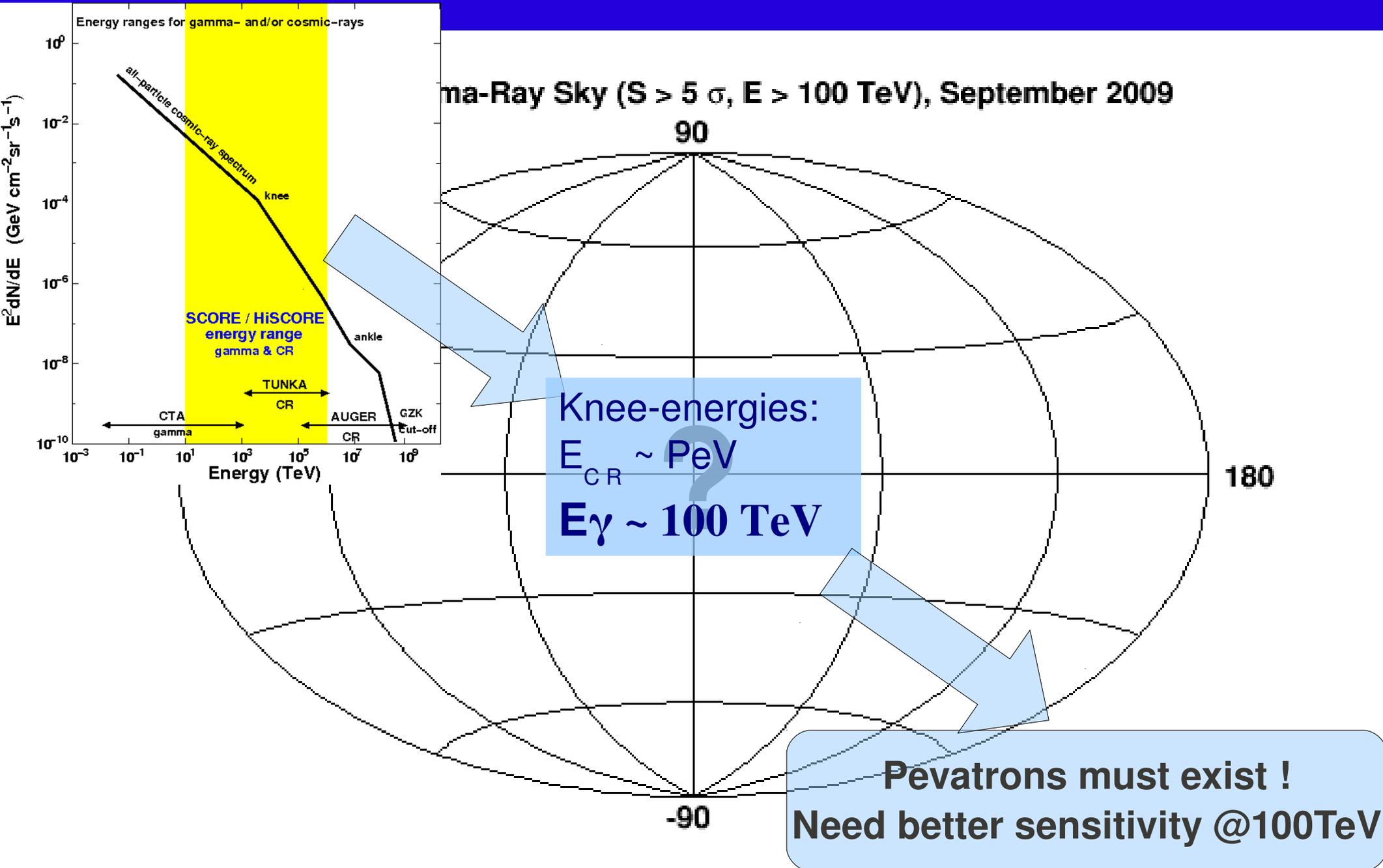
Gamma-Ray Sky, $E > 100 \text{ TeV}$



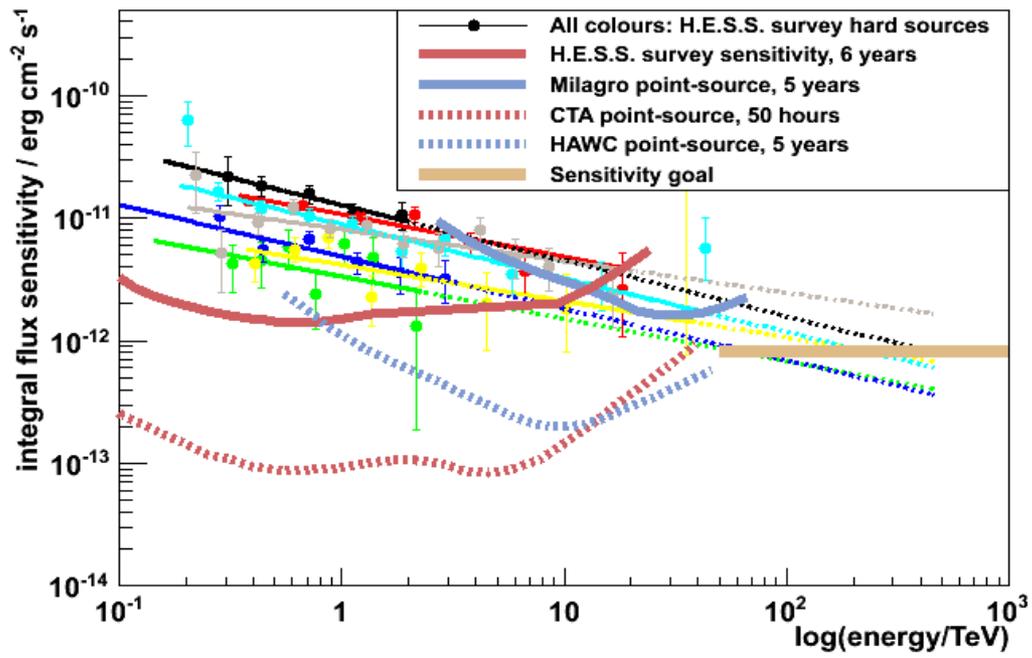
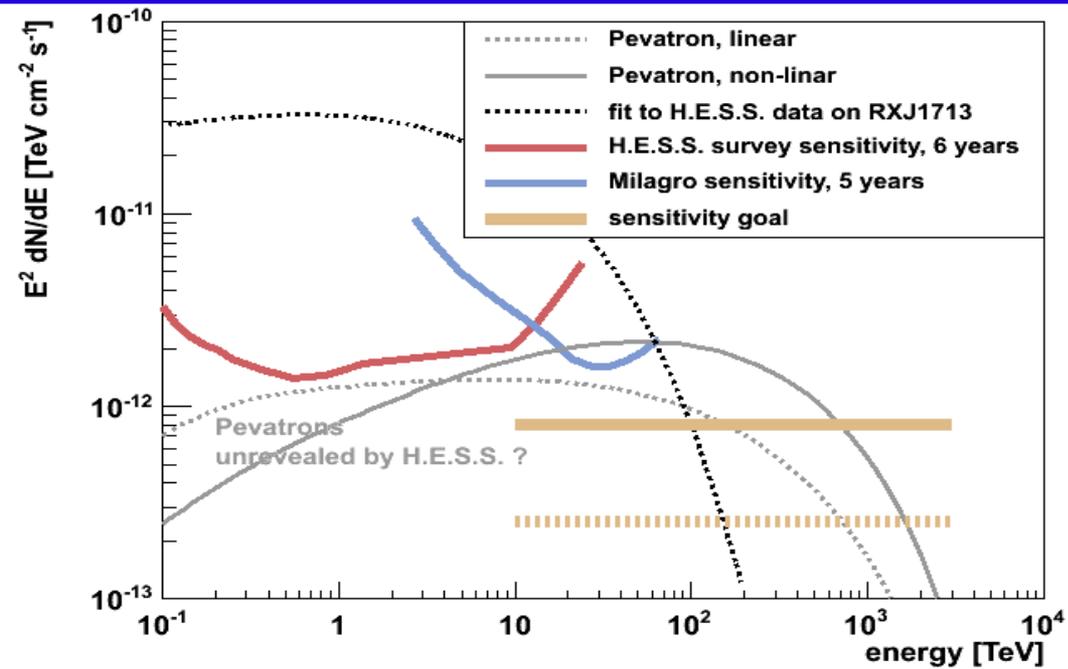
Gamma-Ray Sky, $E > 100 \text{ TeV}$



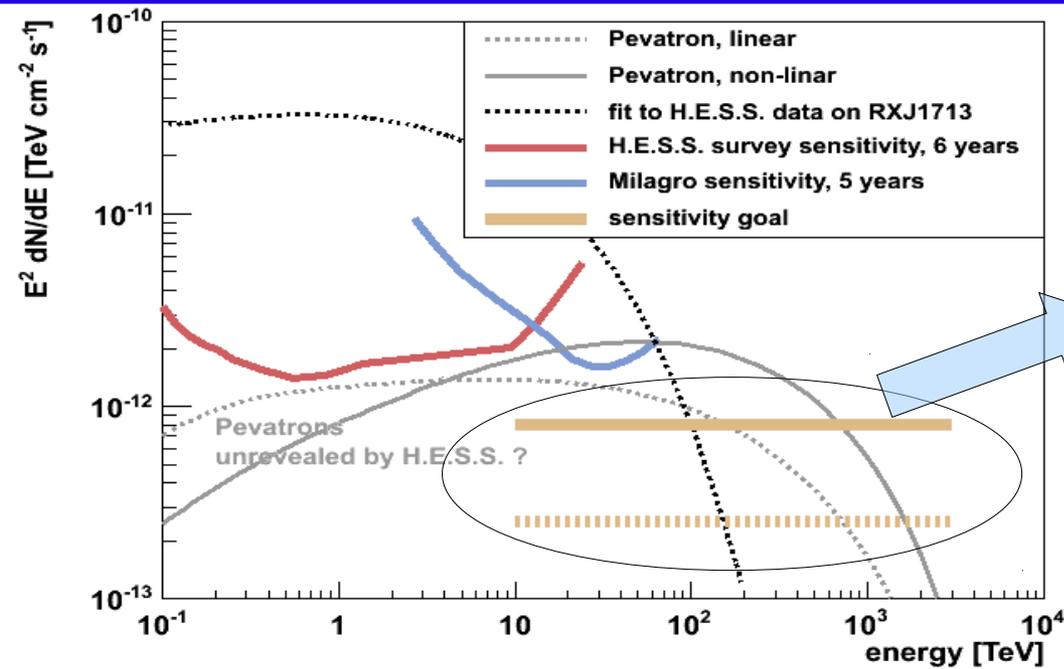
Gamma-Ray Sky, $E > 100 \text{ TeV}$



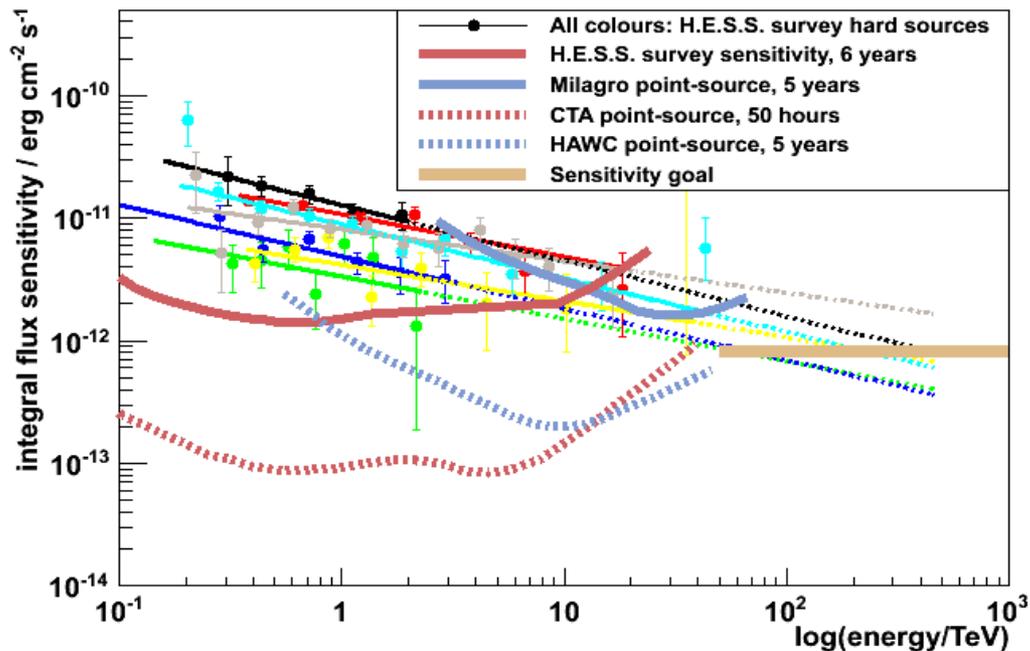
Motivations



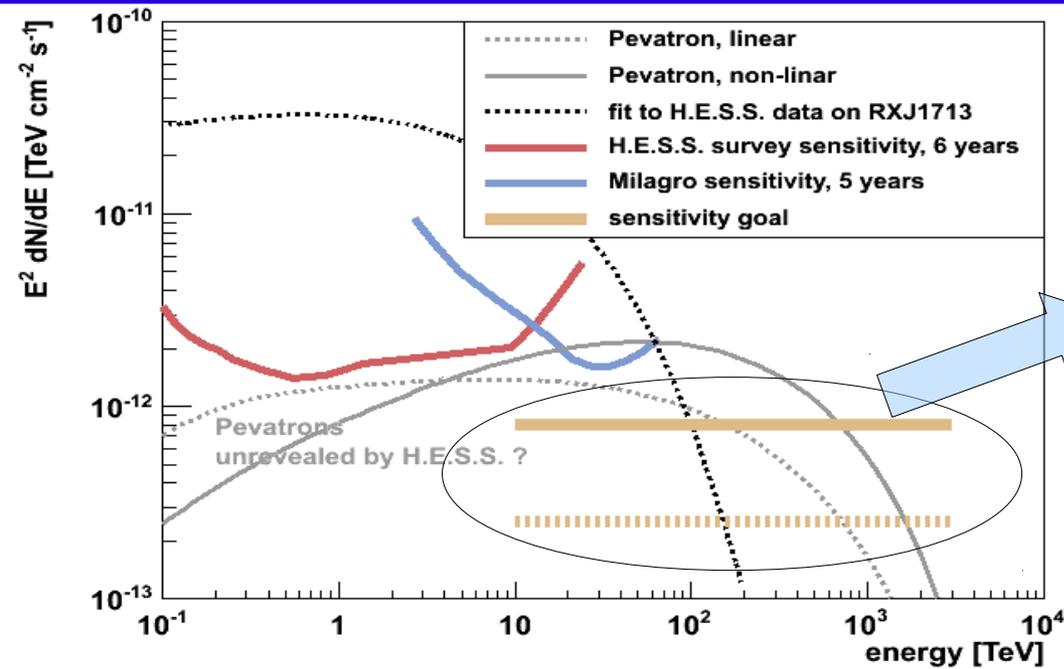
Motivations



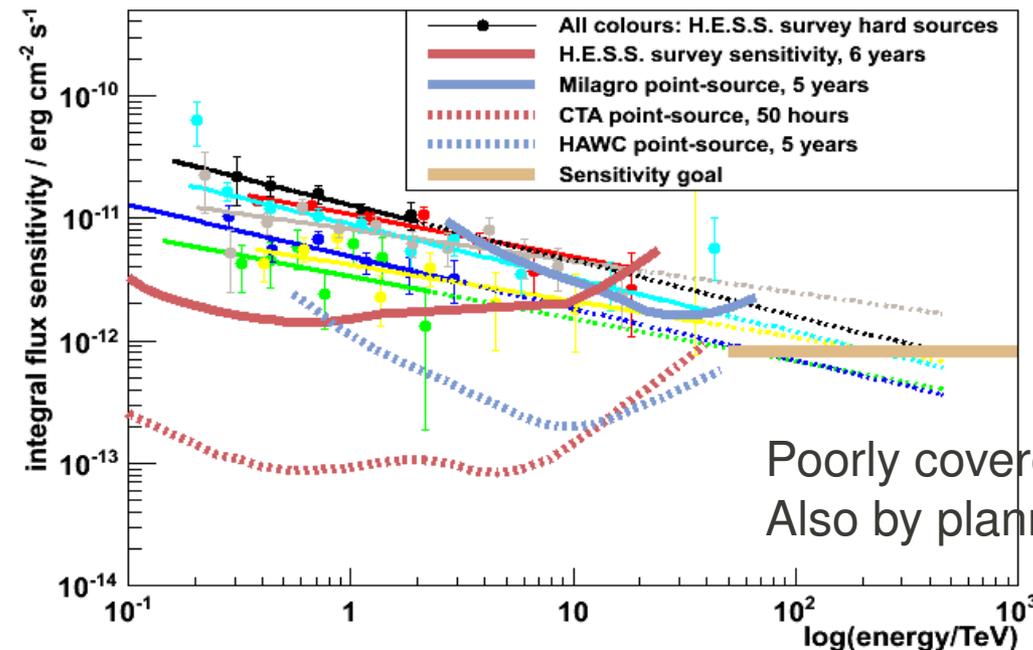
Extend energy range to multi-PeV
Need a large area !



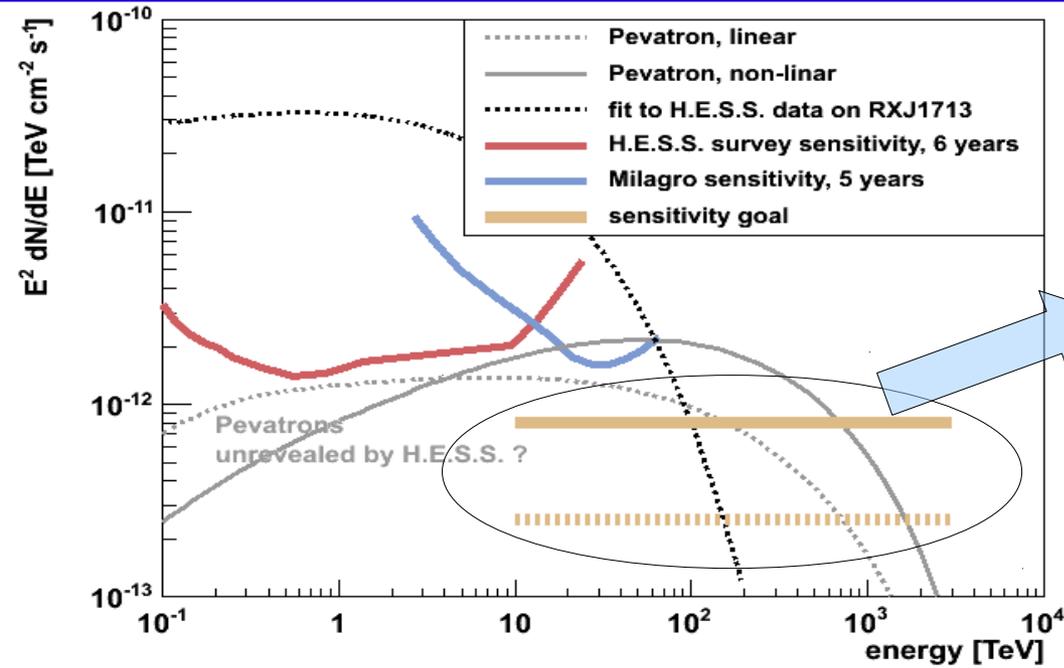
Motivations



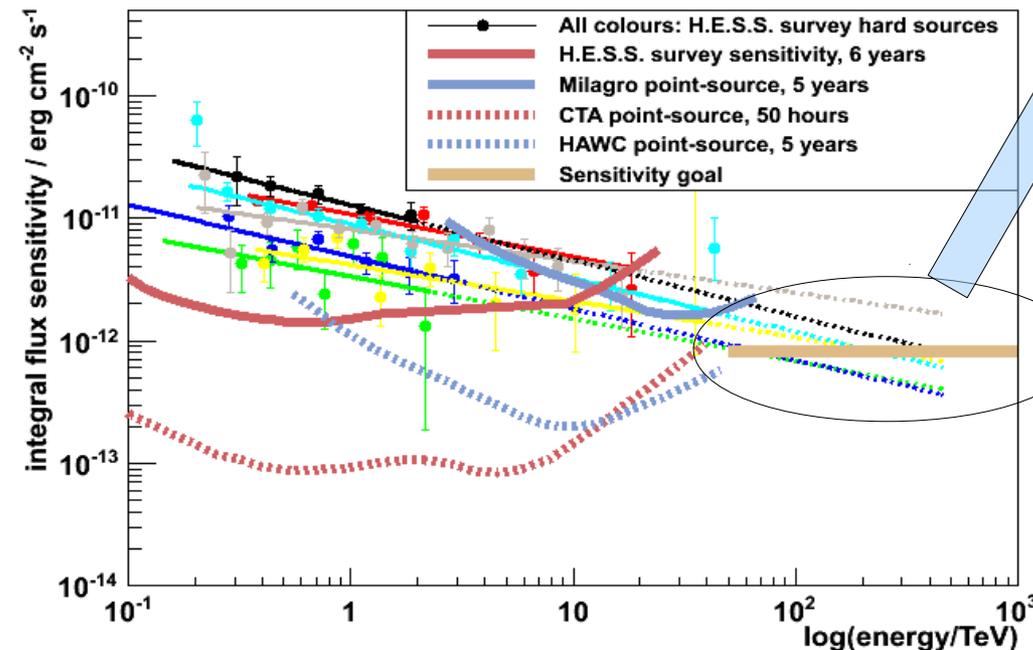
Extend energy range to multi-PeV
Need a large area !



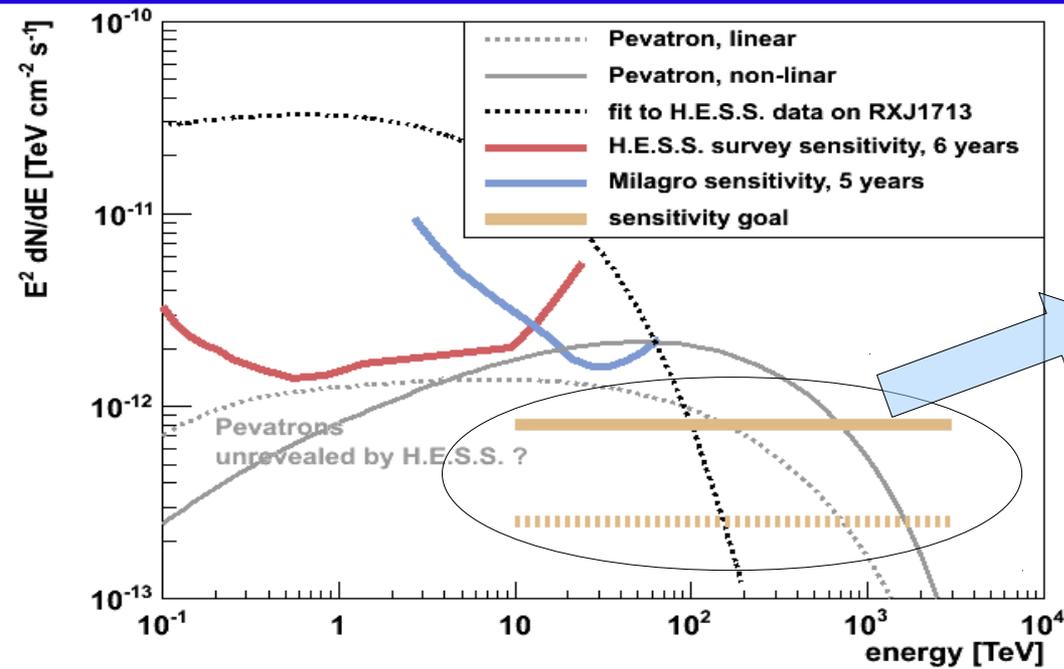
Motivations



Extend energy range to multi-PeV
Need a large area !

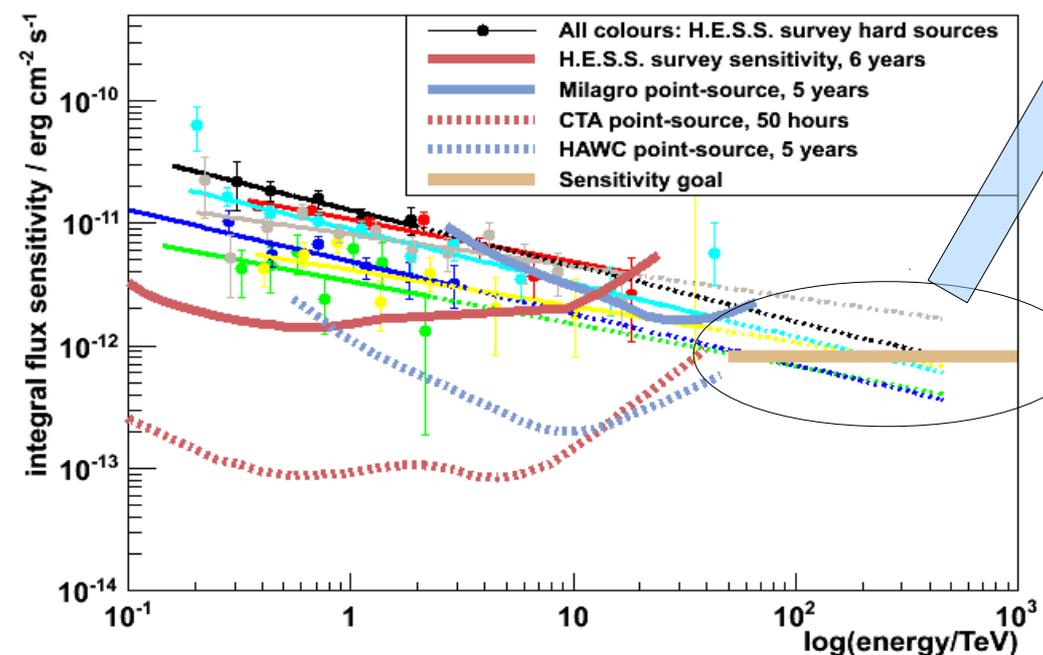


Motivations

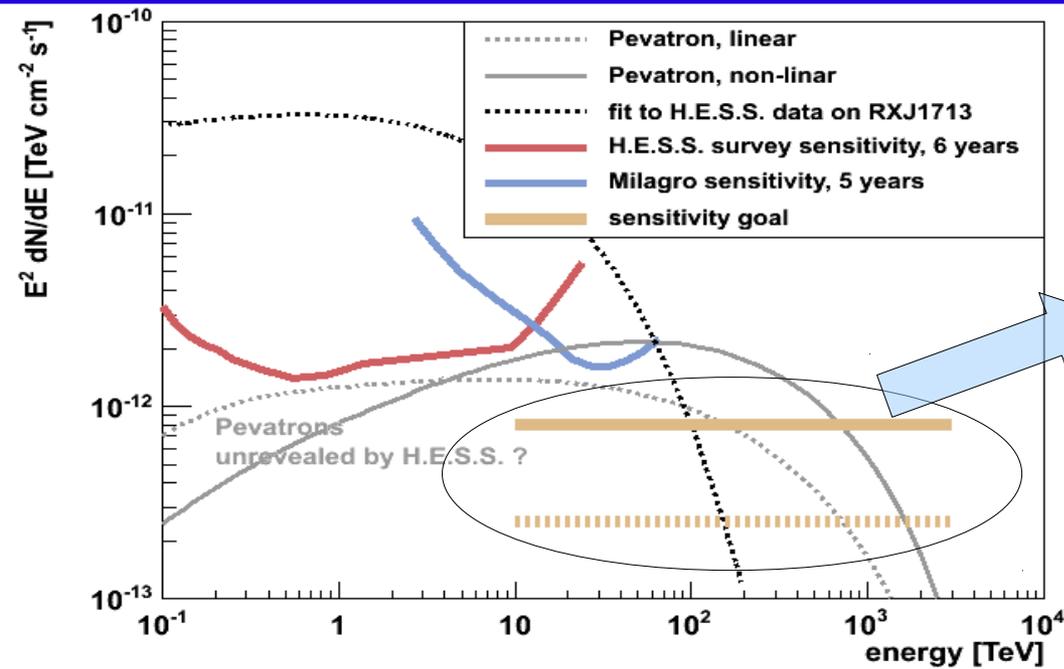


Extend energy range to multi-PeV
Need a large area !

Bonus: unambiguous signal !
No hard IC emission beyond 100 TeV
(Klein-Nishina regime)

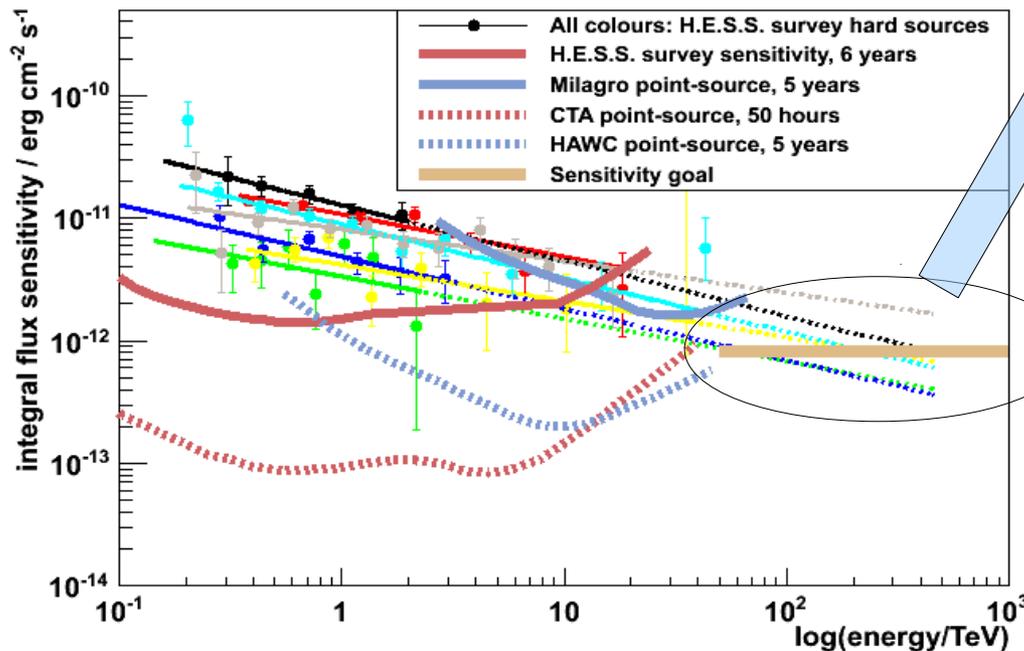


Motivations

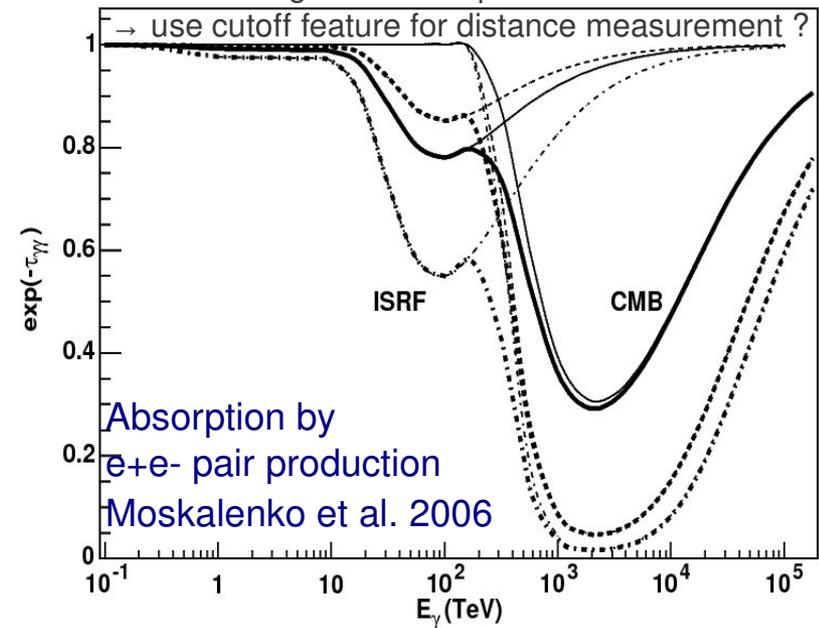


Extend energy range to multi-PeV
Need a large area !

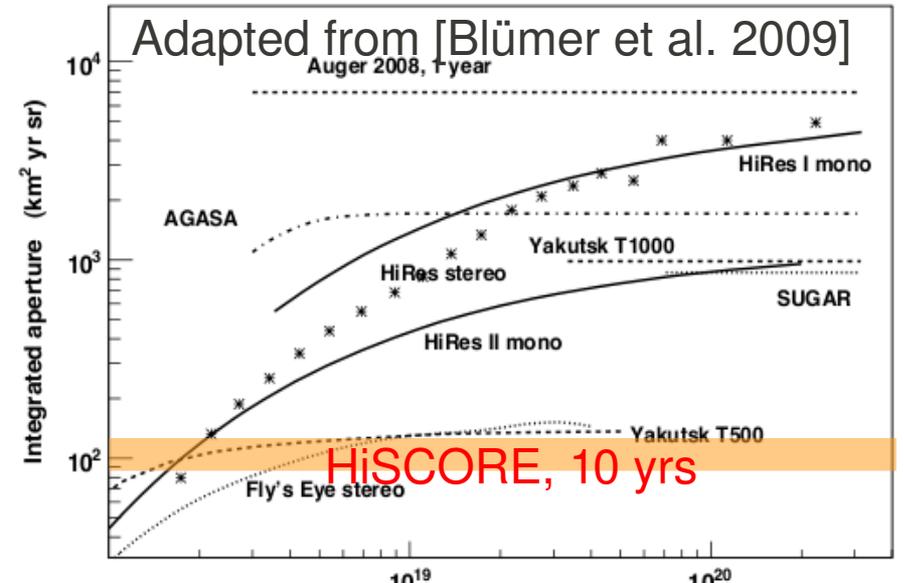
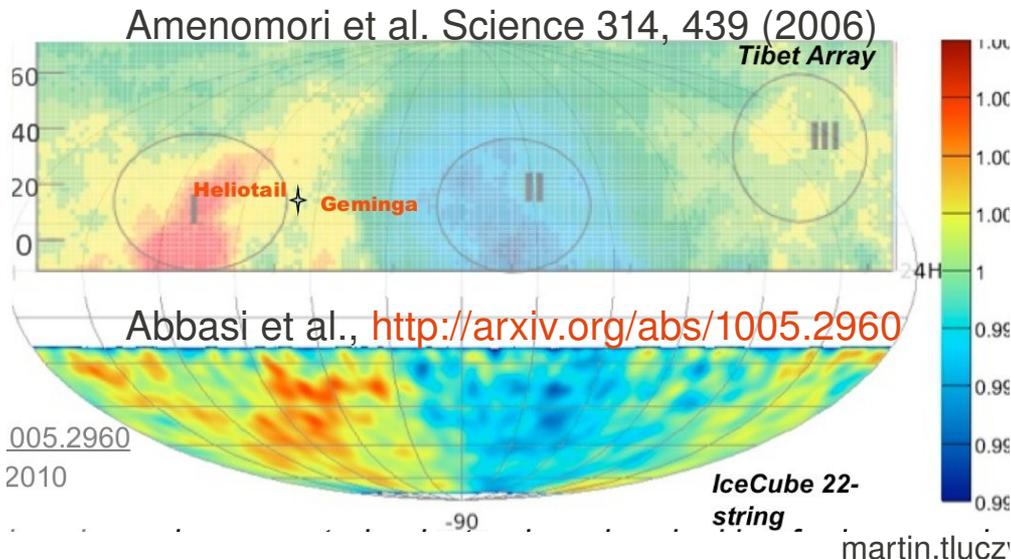
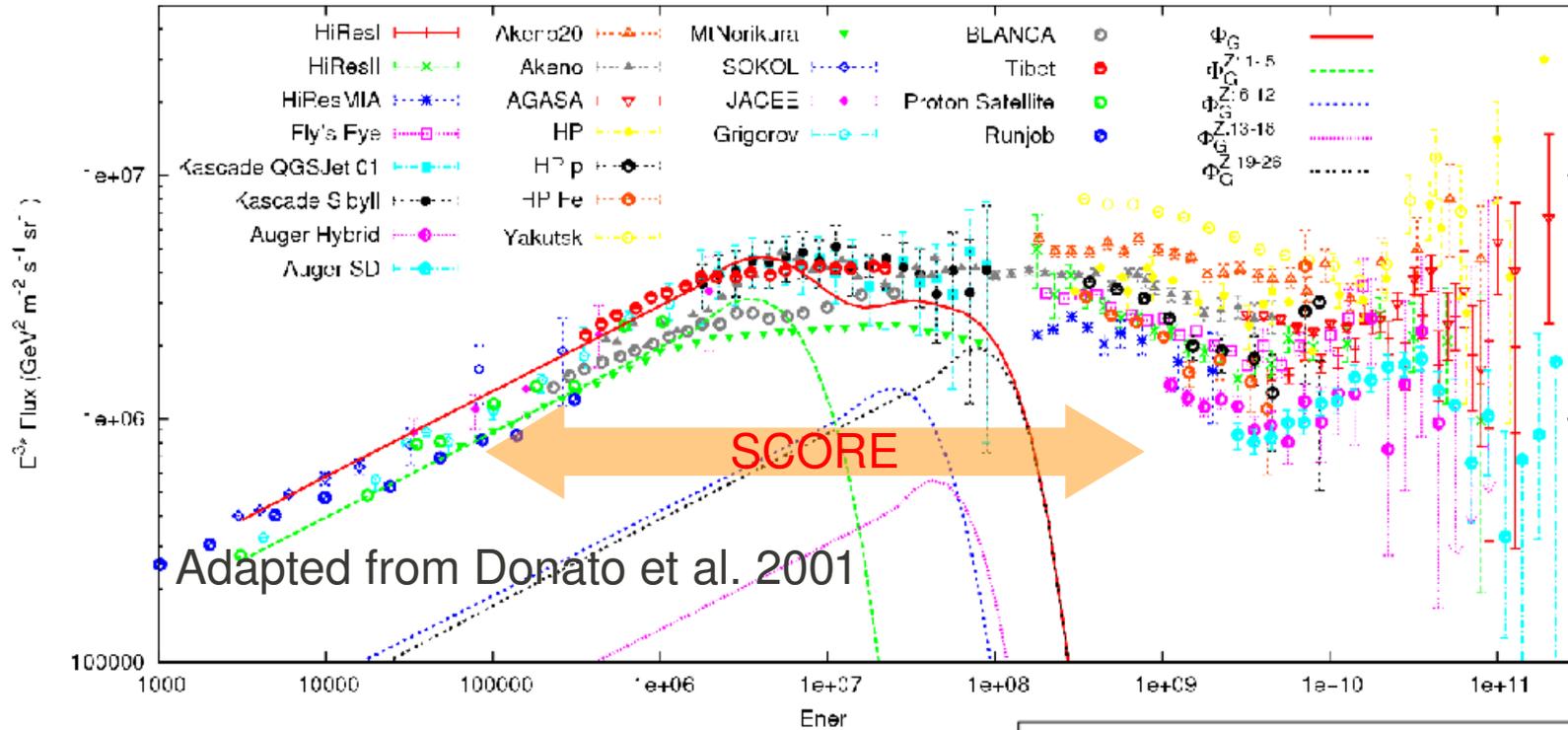
Bonus: unambiguous signal !
No hard IC emission beyond 100 TeV
(Klein-Nishina regime)



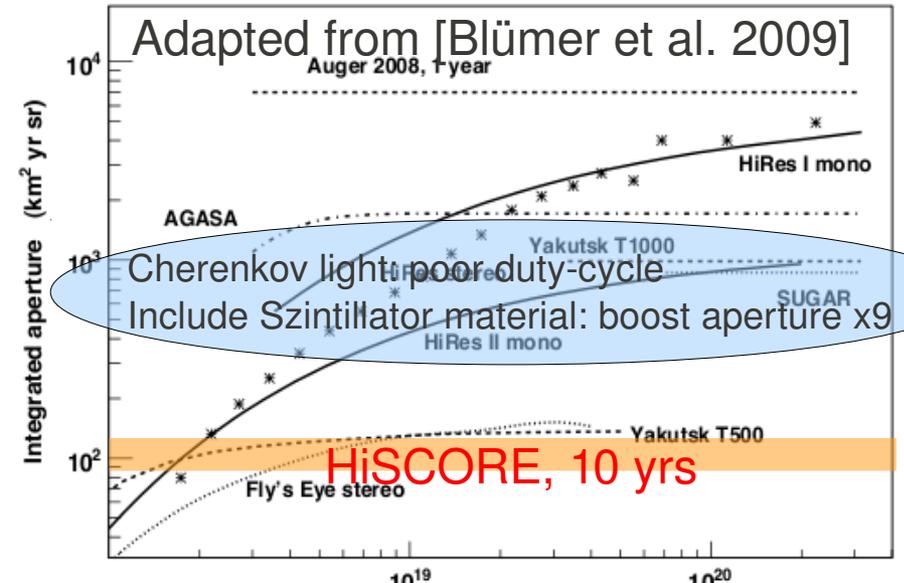
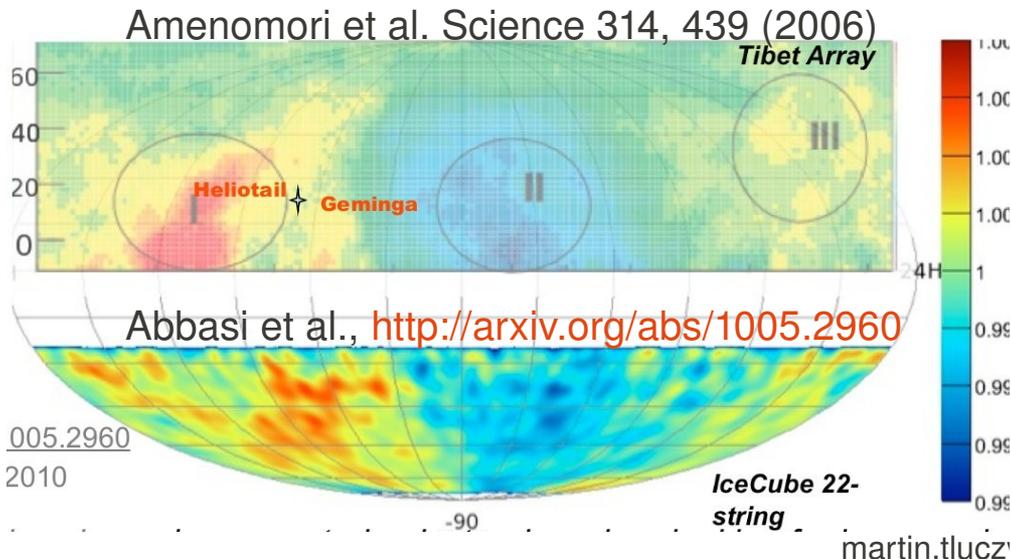
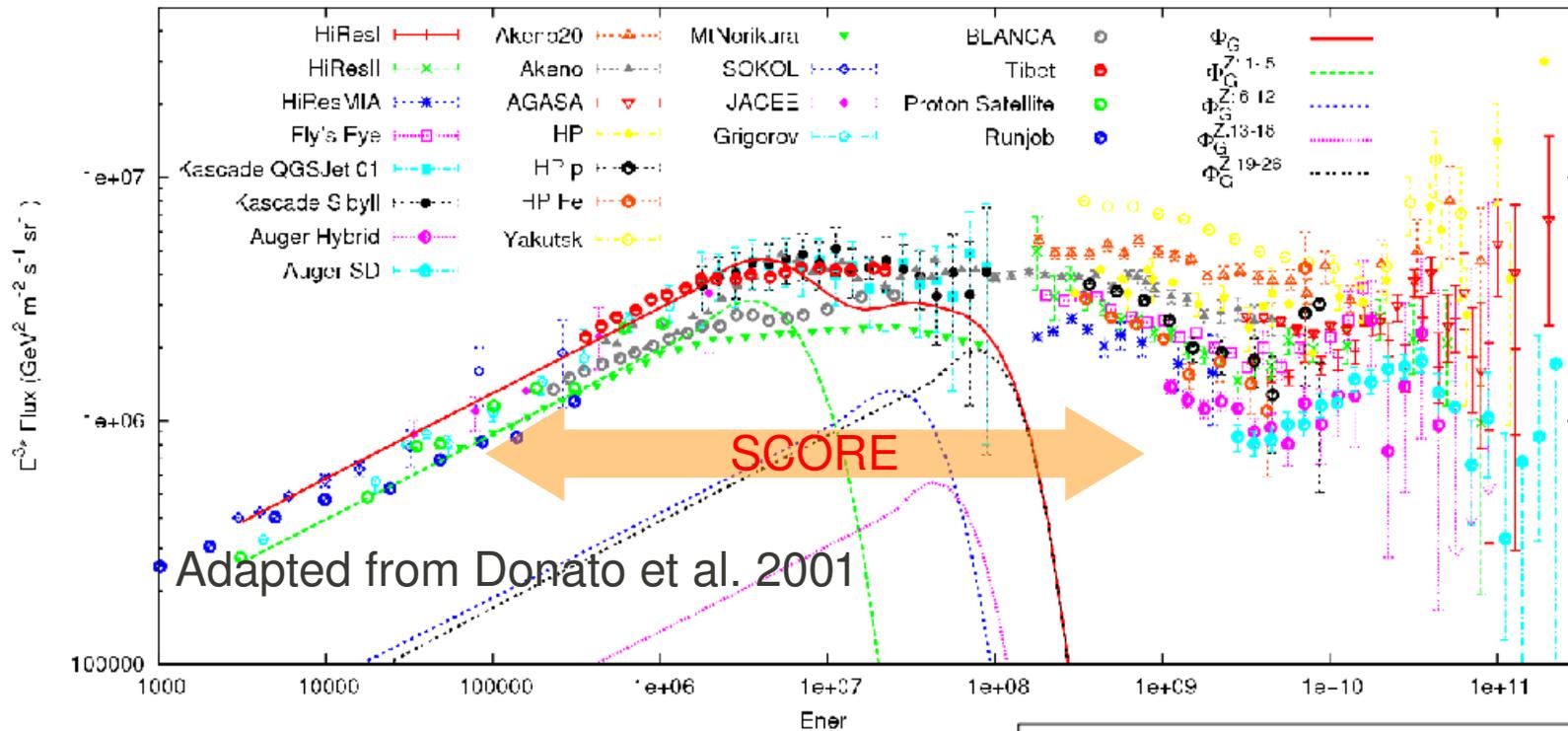
$E \sim 100 \text{ TeV}$: absorption in ISRF relevant
 $E \sim 1 \text{ PeV}$: strong CMB absorption



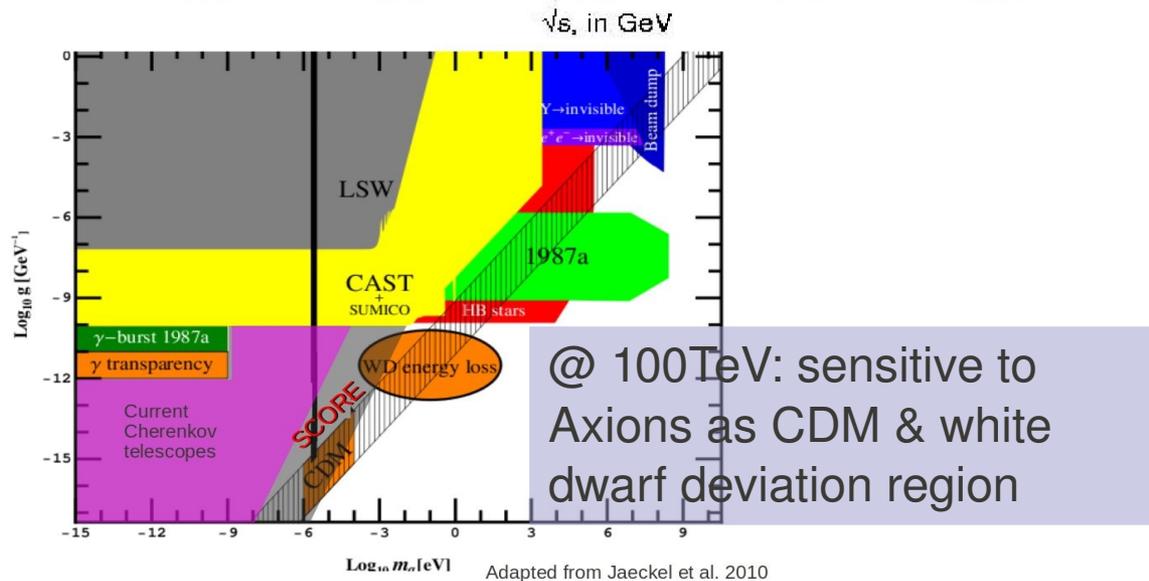
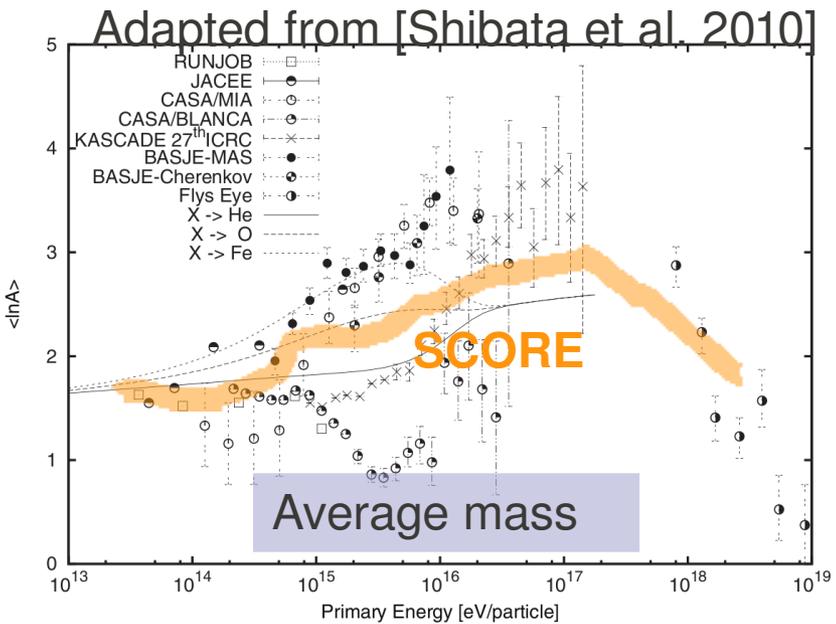
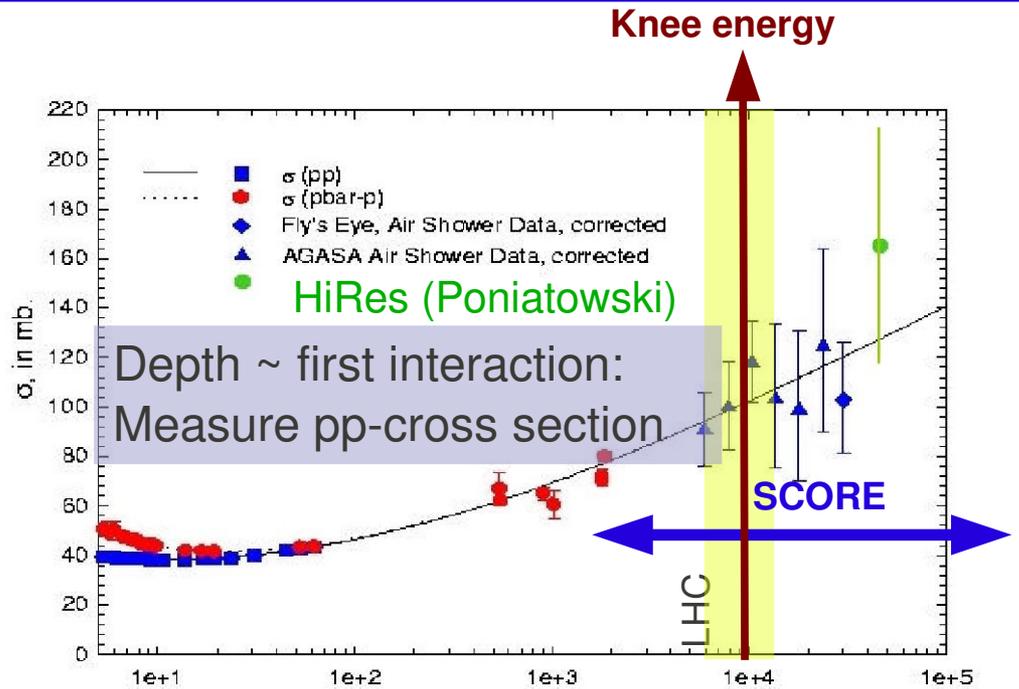
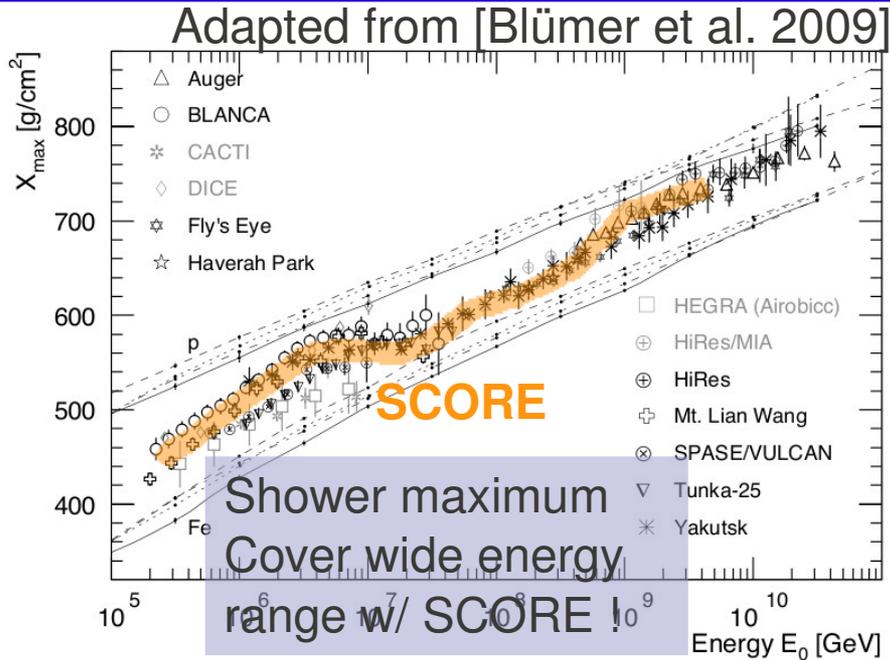
Motivations



Motivations



Motivations



The detector

Goals:

Energy range goal: 10 TeV – 1 EeV

Area goal: 10 – 100+ km²

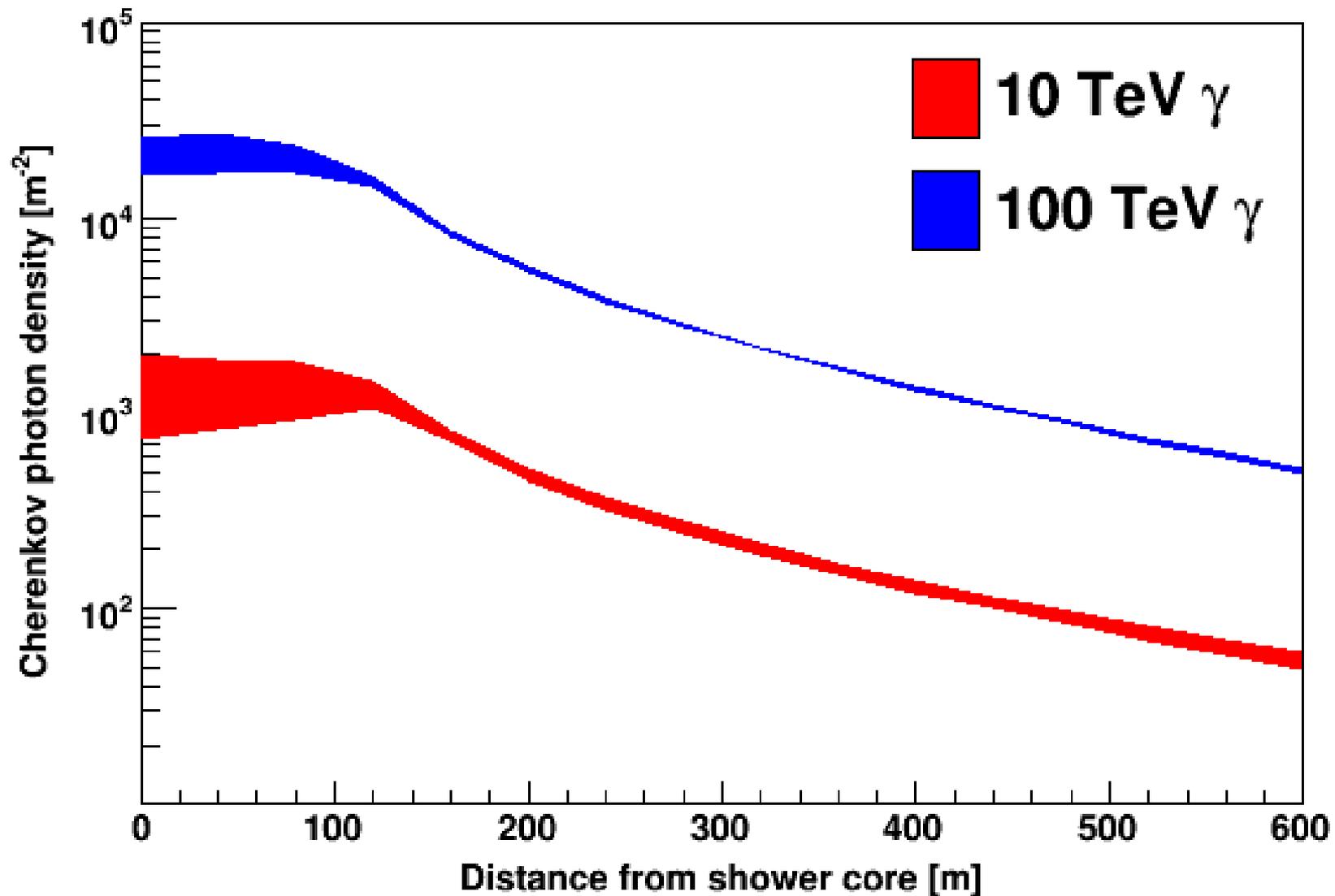
Sensitivity goal: better than 10^{-12} erg / cm² s

Concept:

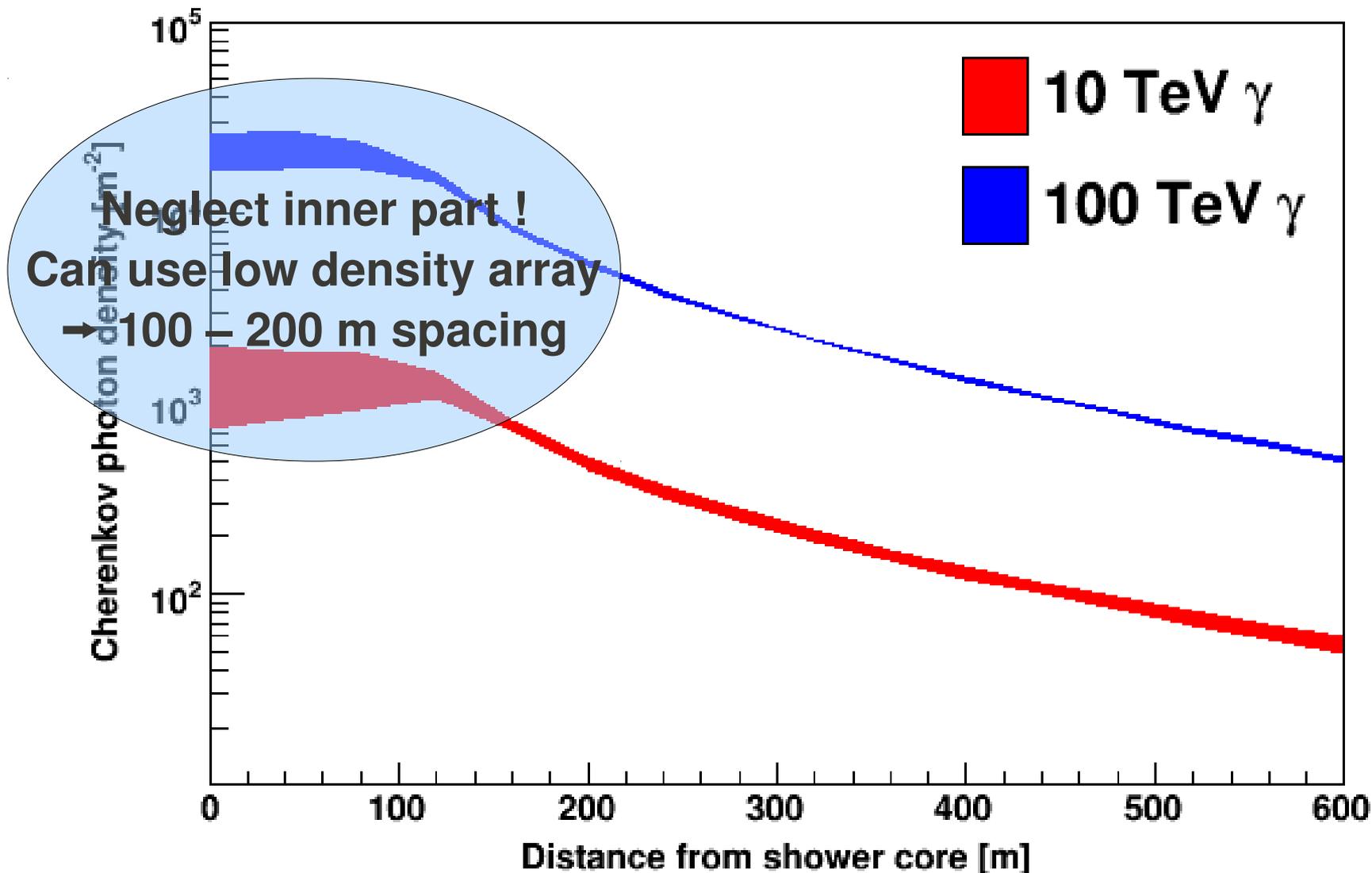
Large effective area, wide field of view

Non-imaging atmospheric Cherenkov technique

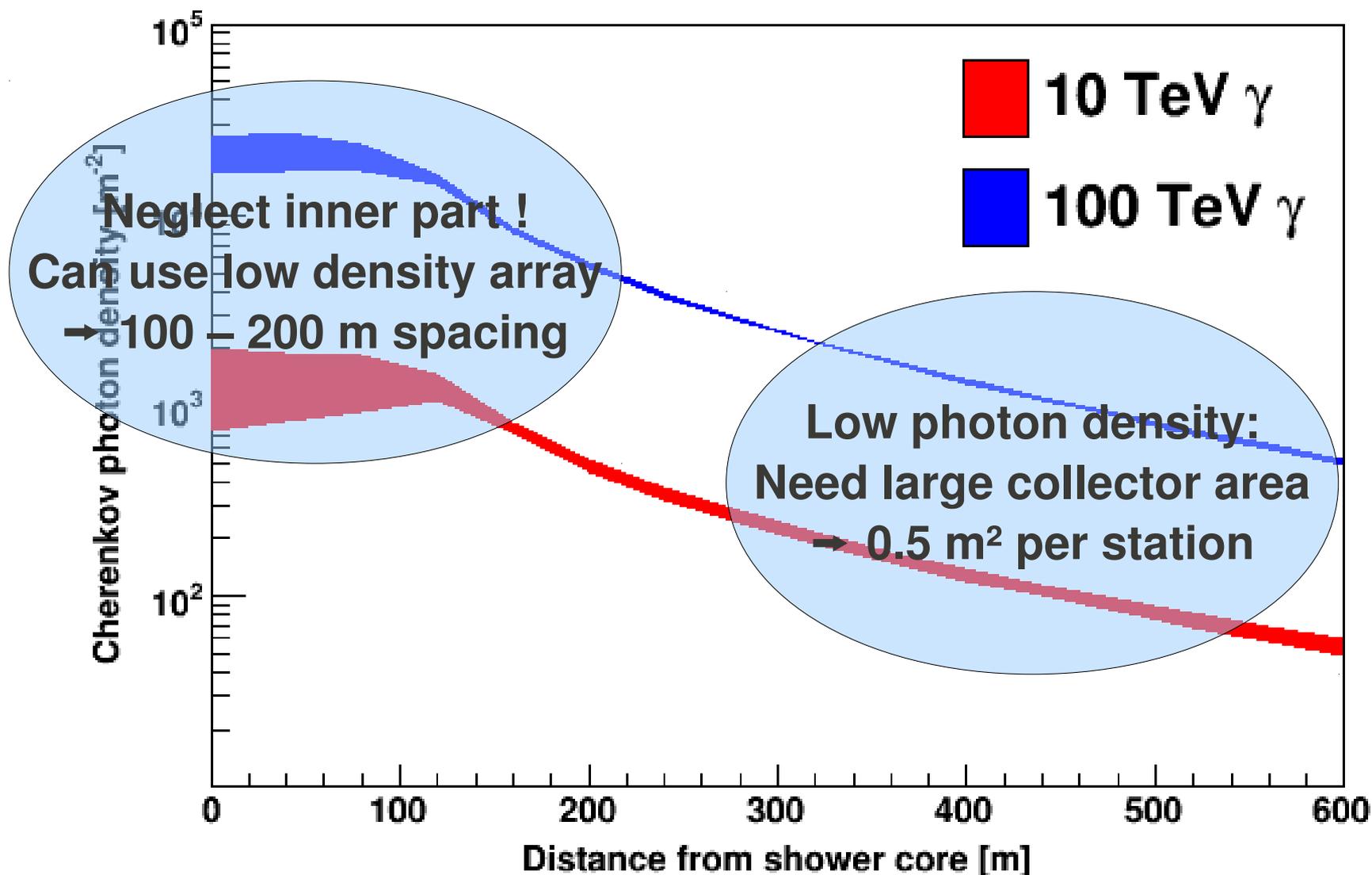
Lateral Cherenkov Photon Distribution



Lateral Cherenkov Photon Distribution



Lateral Cherenkov Photon Distribution



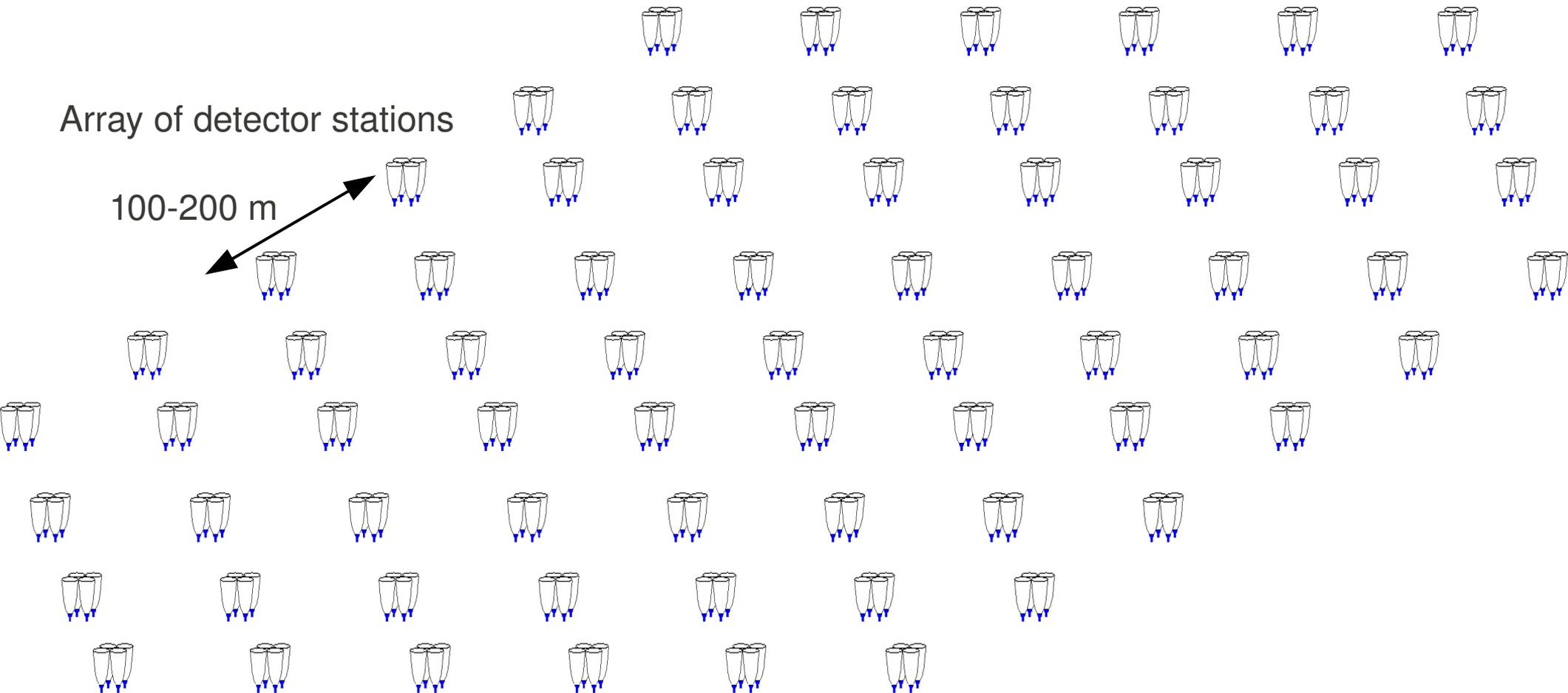
The SCORE principle

Ultra-High energy regime: **need large effective area !**

Imaging ACTs: > 10000 channels / km^2

Non-imaging Cherenkov light-front sampling

SCORE: < 100 channels / km^2



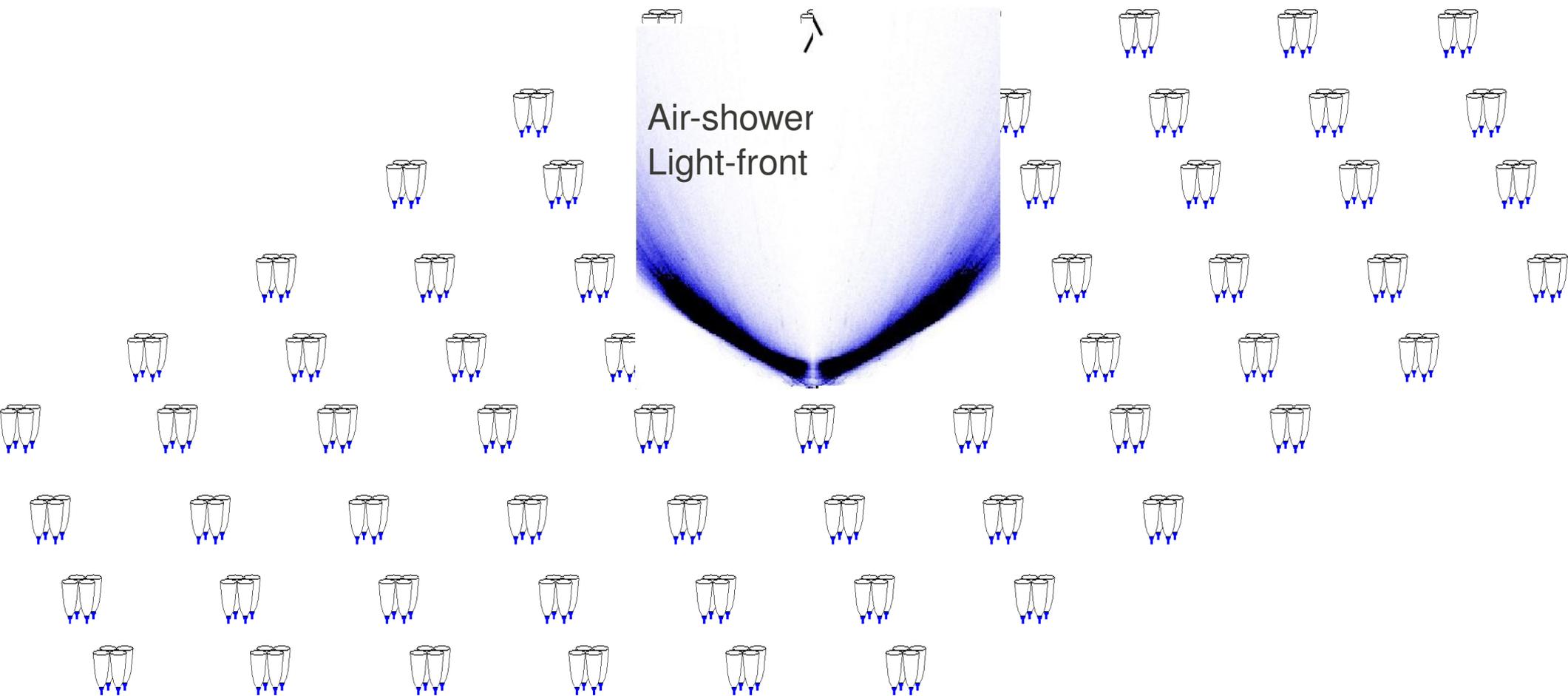
The SCORE principle

Ultra-High energy regime: **need large effective area !**

Imaging ACTs: > 10000 channels / km²

Non-imaging Cherenkov light-front sampling – record light amplitude and timing

SCORE: < 100 channels / km²



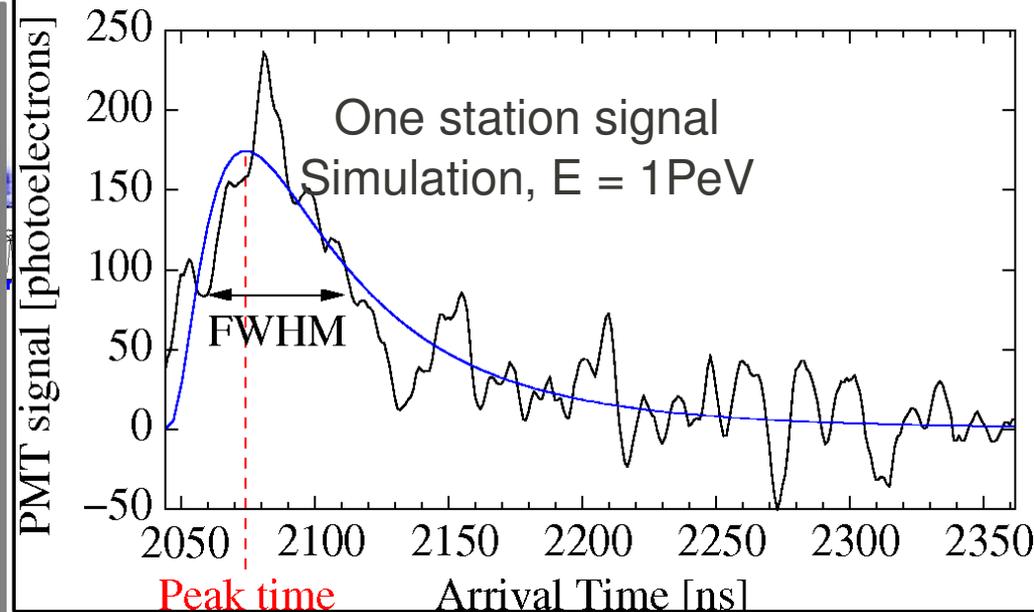
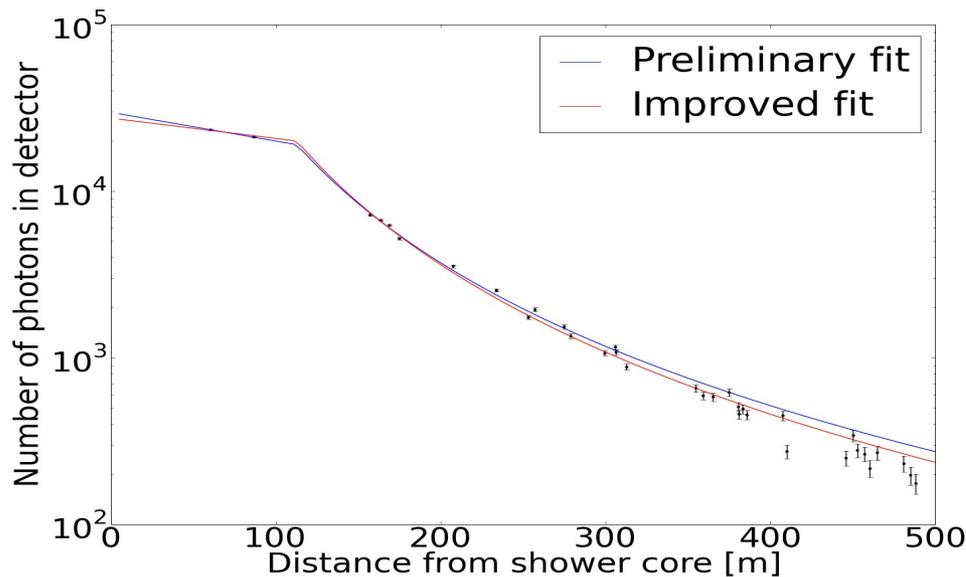
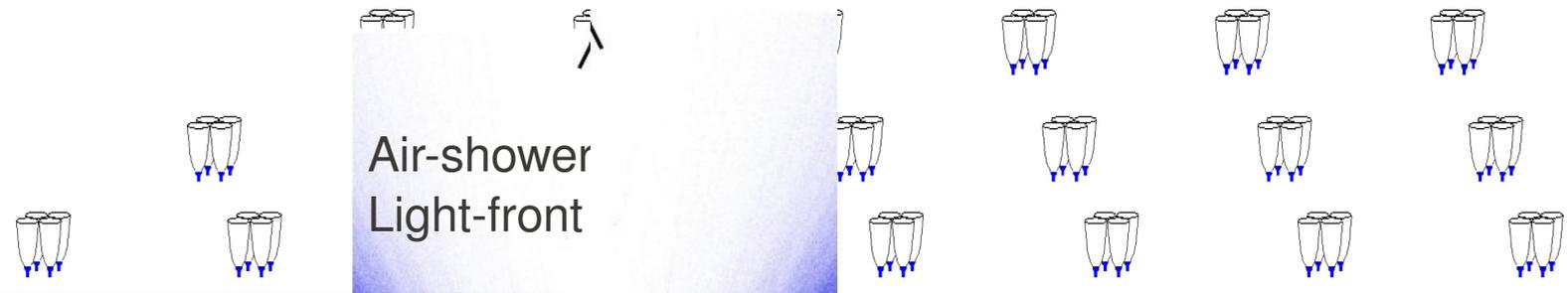
The SCORE principle

Ultra-High energy regime: **need large effective area !**

Imaging ACTs: > 10000 channels / km^2

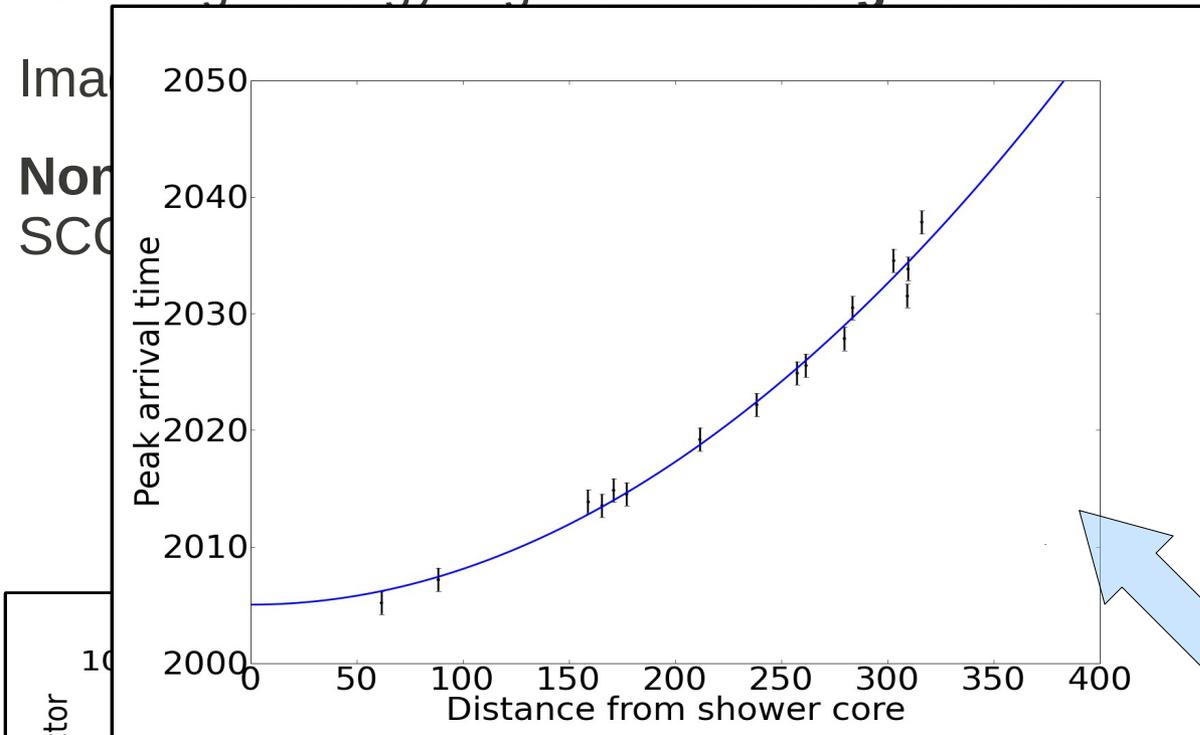
Non-imaging Cherenkov light-front sampling – record light amplitude and timing

SCORE: < 100 channels / km^2

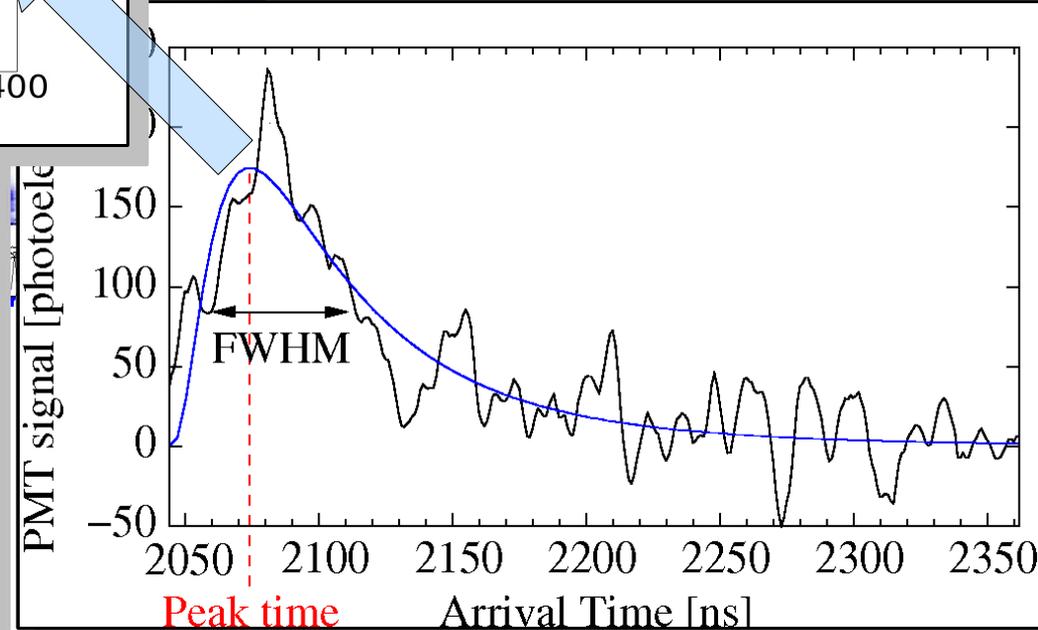
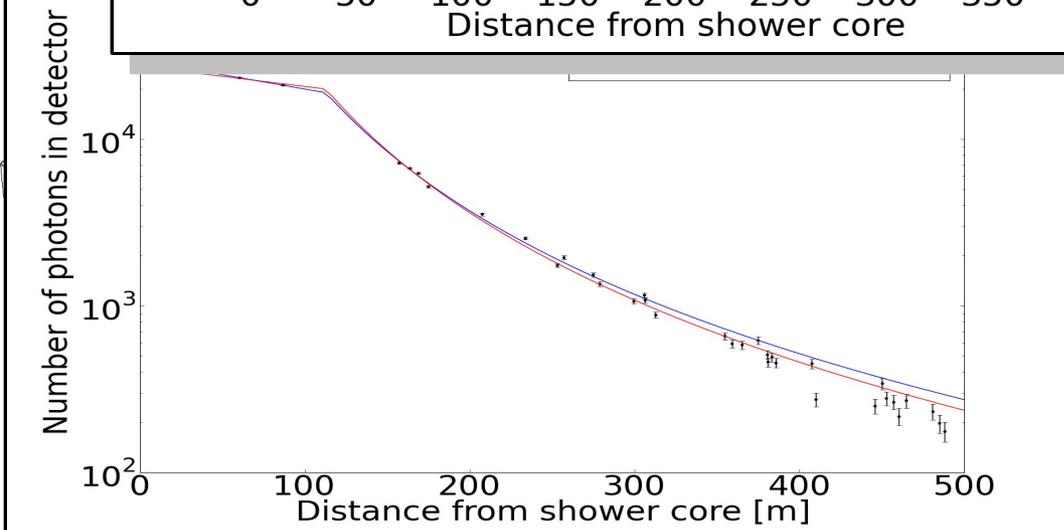
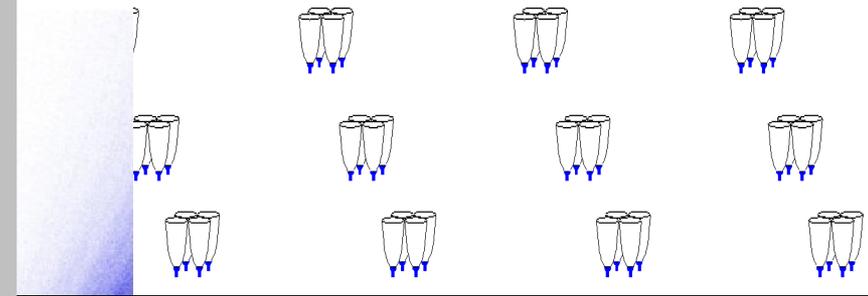


The SCORE principle

Ultra-High energy regime: need large effective area !



record light amplitude and timing



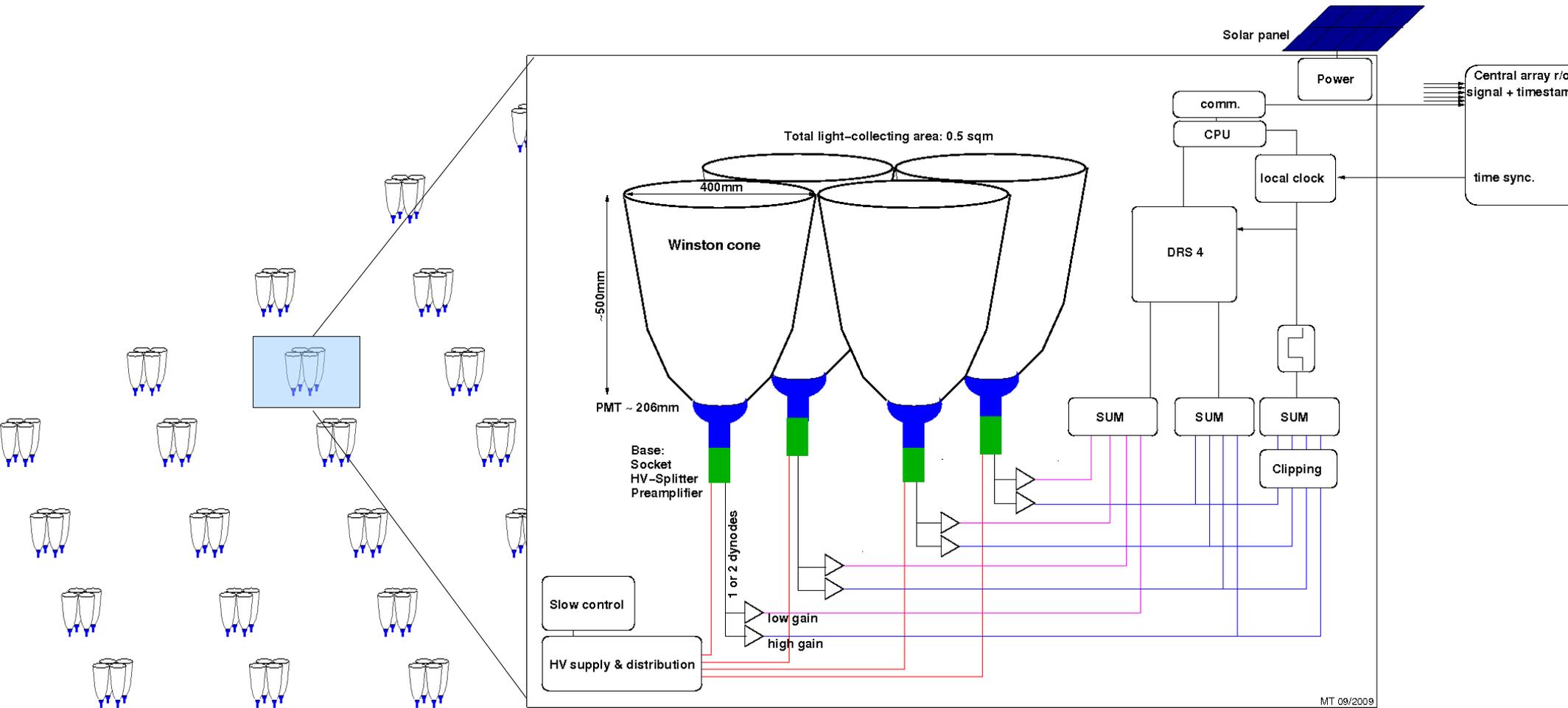
The SCORE principle

Ultra-High energy regime: **need large effective area !**

Imaging ACTs: > 10000 channels / km^2

Non-imaging Cherenkov light-front sampling – record light amplitude and timing

SCORE: < 100 channels / km^2



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 8" PMT, data sheet)
Electron collection efficiency included
PMT signal pulse-shape parameterization [4]
Afterpulsing simulated w/ $P = 10^{-4}$ at 4 p.e.
Local trigger: 4-channel coincidence
Array trigger: 1-station or 2-station NN (1 μ s coincidence window)
Night-sky background (including pulse shaping), added to signals

Expected night-sky background trigger rate

Simulation of 4-channel station:

NSB-rate from measurement in Australia

→ Cooperation with Adelaide group

See Poster by D. Hampf et al. !

Arrays of Photon times: equally distributed random numbers

Use pulse shaping following Parametrization for ET9352 (V. Henke 1994, U. of Hamburg)

Random amplitude including afterpulses

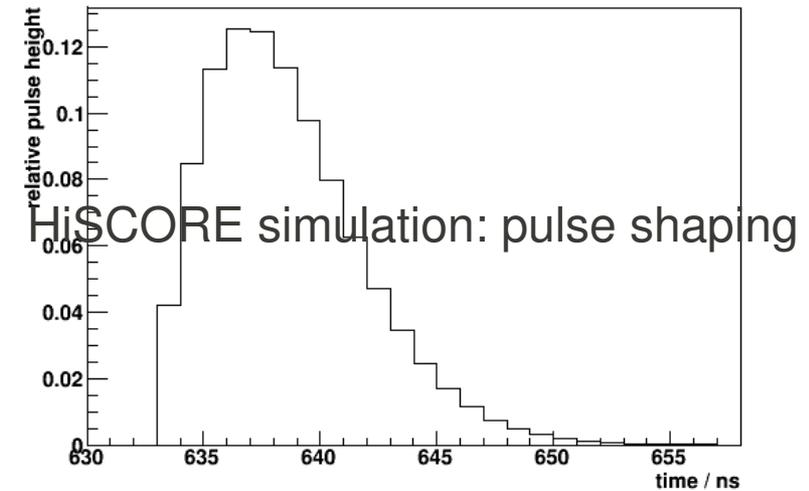
Level-1 trigger: 4-channel coincidence

→ channel-amplitude-clipping

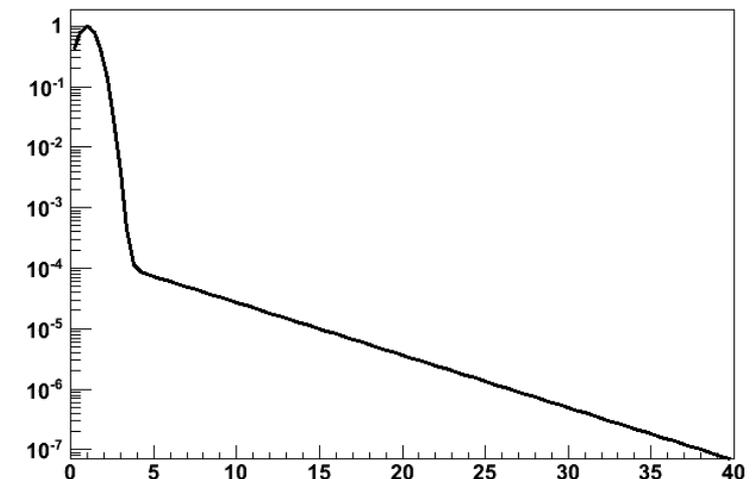
→ analog sum of 4 clipped signals

→ Discriminate analog sum

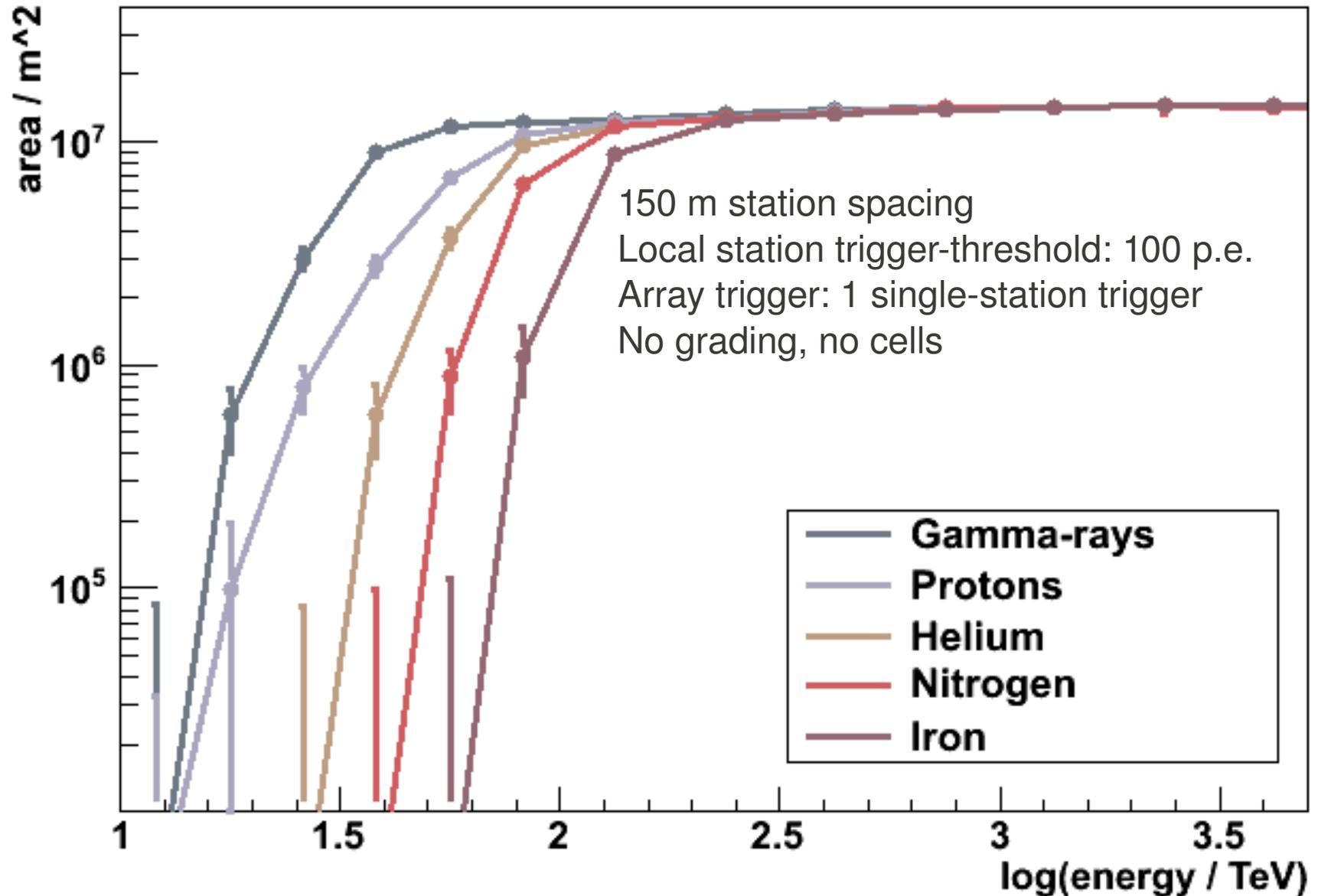
Level-2 trigger: 2-station coincidence
(might not be necessary !)



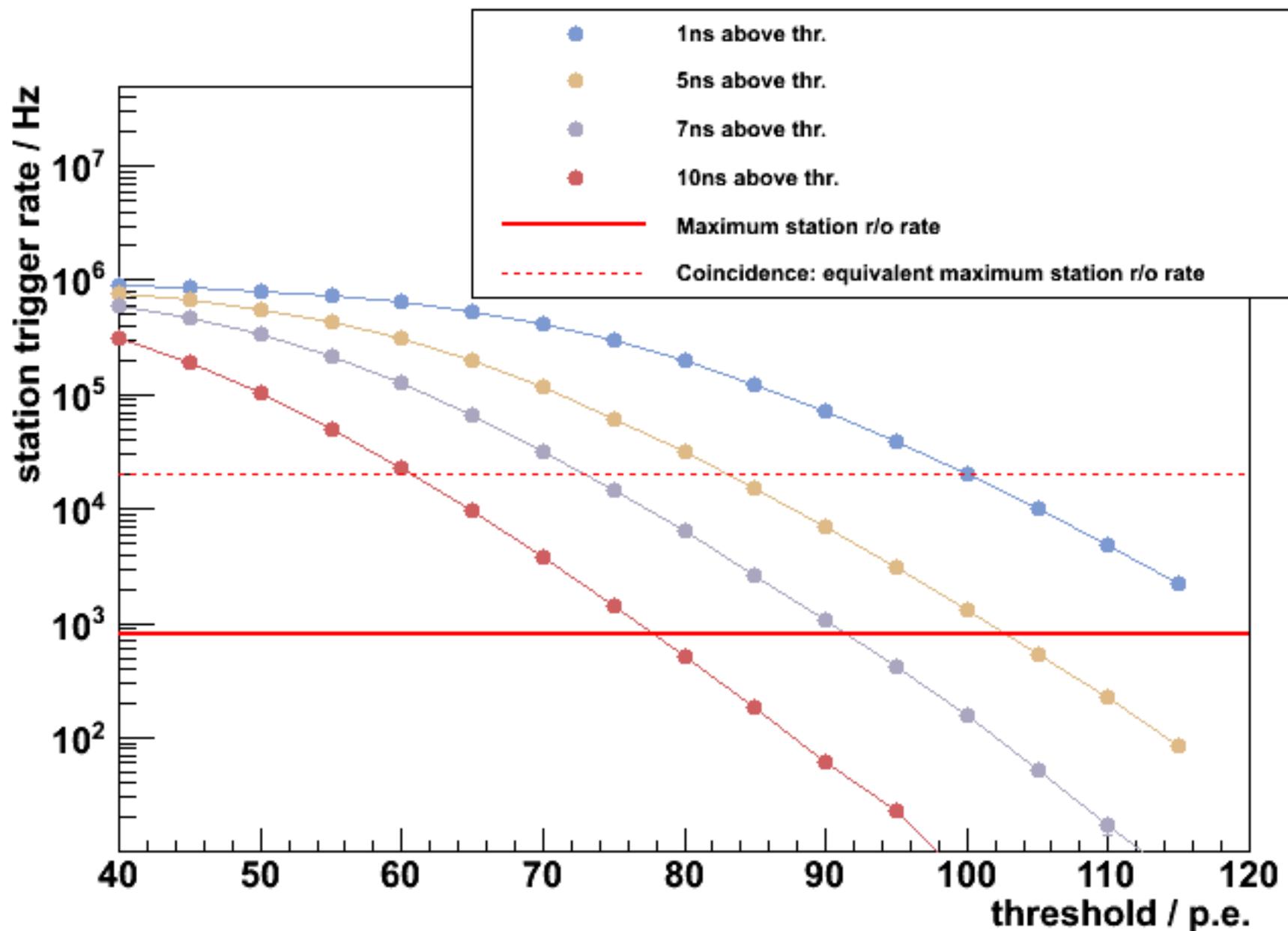
$$2. \cdot 10^{-4} \cdot \exp(-x/5) + \exp(-(x-1) \cdot (x-1) / (2 \cdot 0.6 \cdot 0.6))$$



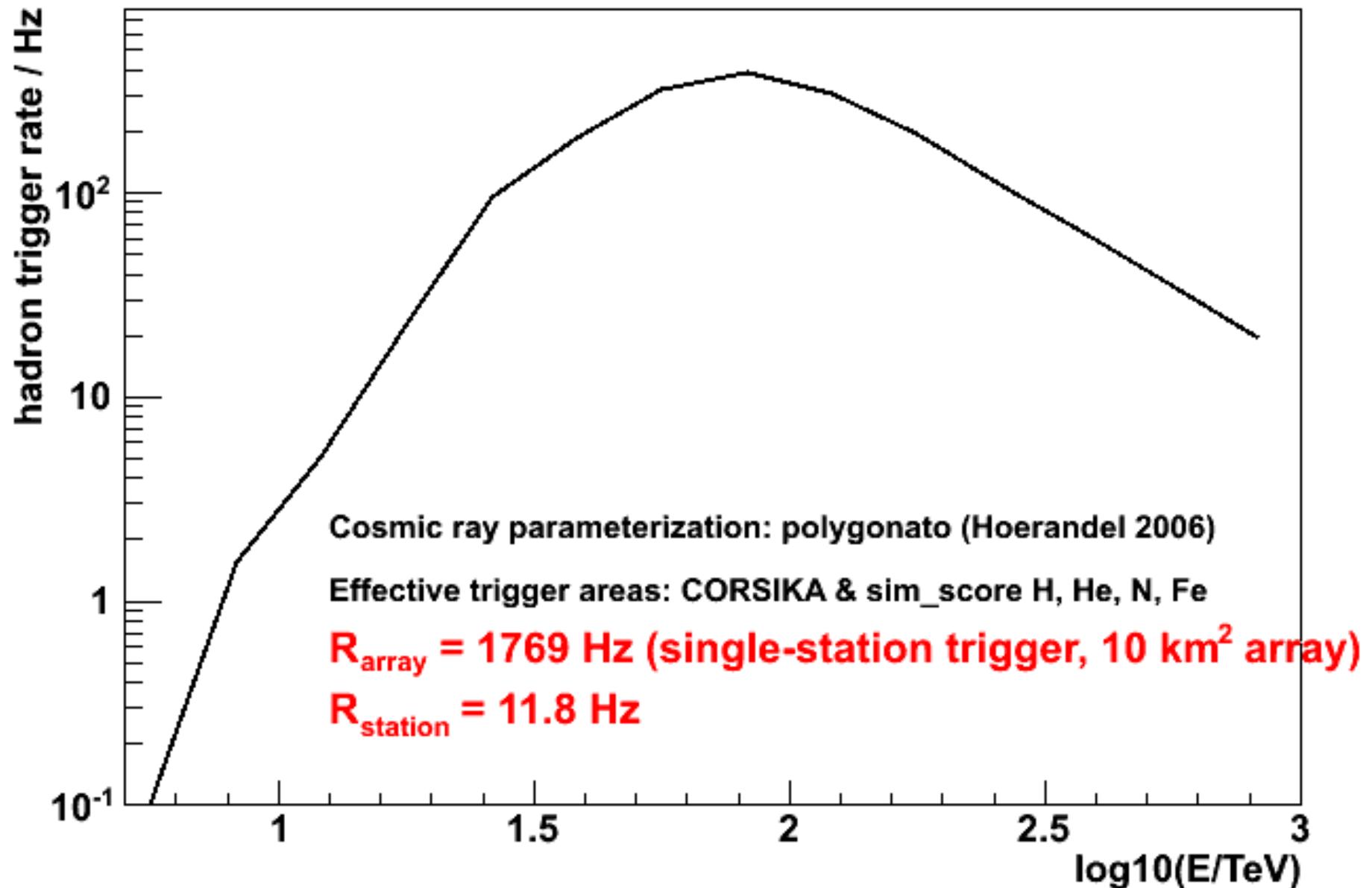
Effective trigger area



Expected night-sky background trigger rate



Expected hadron trigger rate



Trigger rates

Trigger rates for $E > 10$ TeV, before reconstruction cuts

Detector layout: simple grid, 10 km^2 (SCORE)

Trigger condition: single station trigger

protons	774.25 Hz
helium	435.9 Hz
nitrogen	256.5 Hz
iron	89.4 Hz
all-	~1.8 kHz total
particles	~10 Hz / station
NSB:	~1 kHz / station

Performance

Shower core

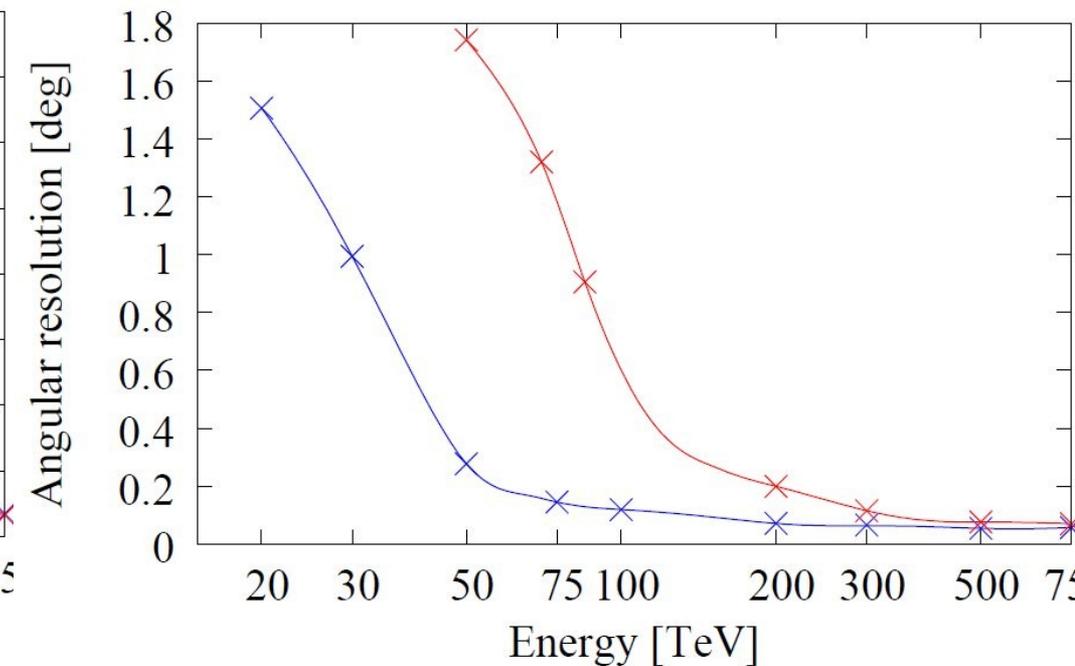
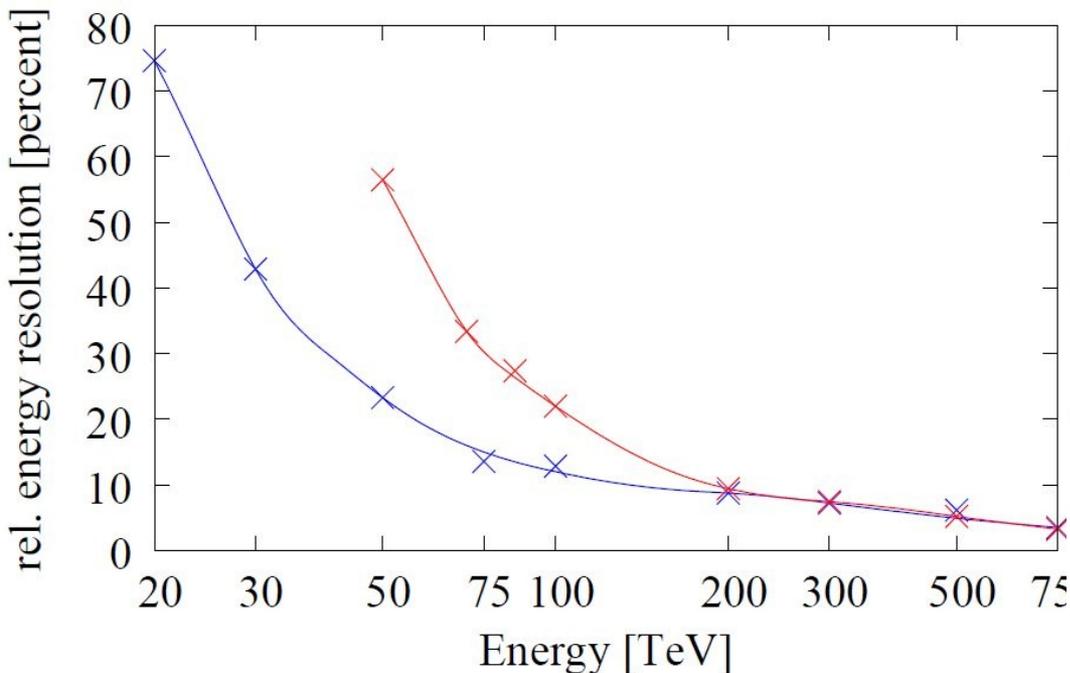
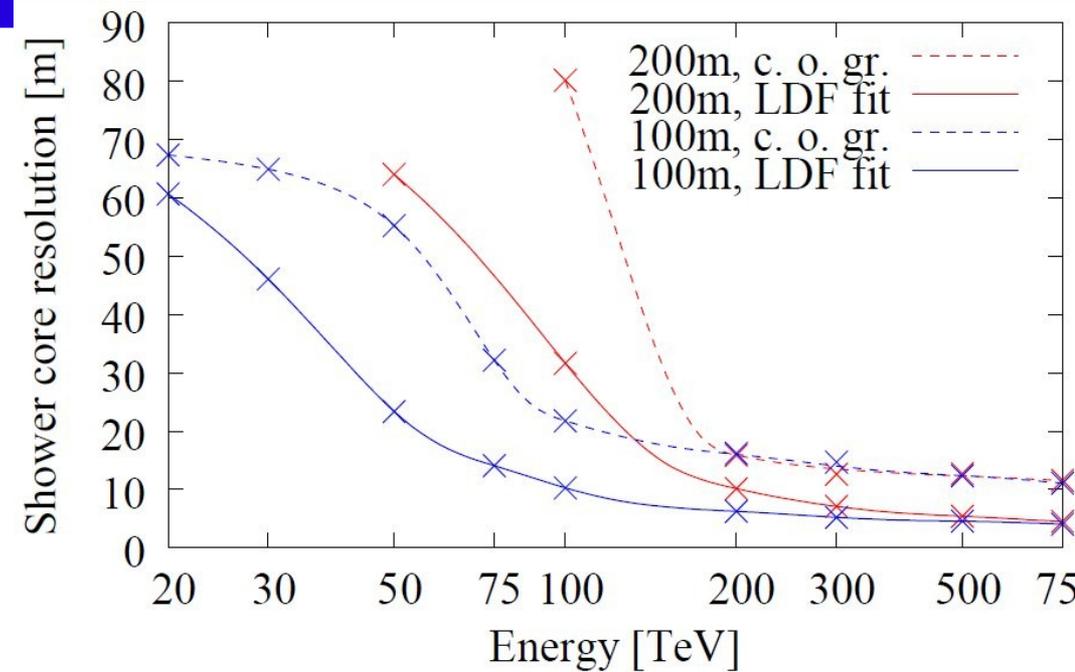
Trivial method: center-of-gravity of light distribution.
Improved method: 2D-fit of lateral density function to station data

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.



Performance

Shower core

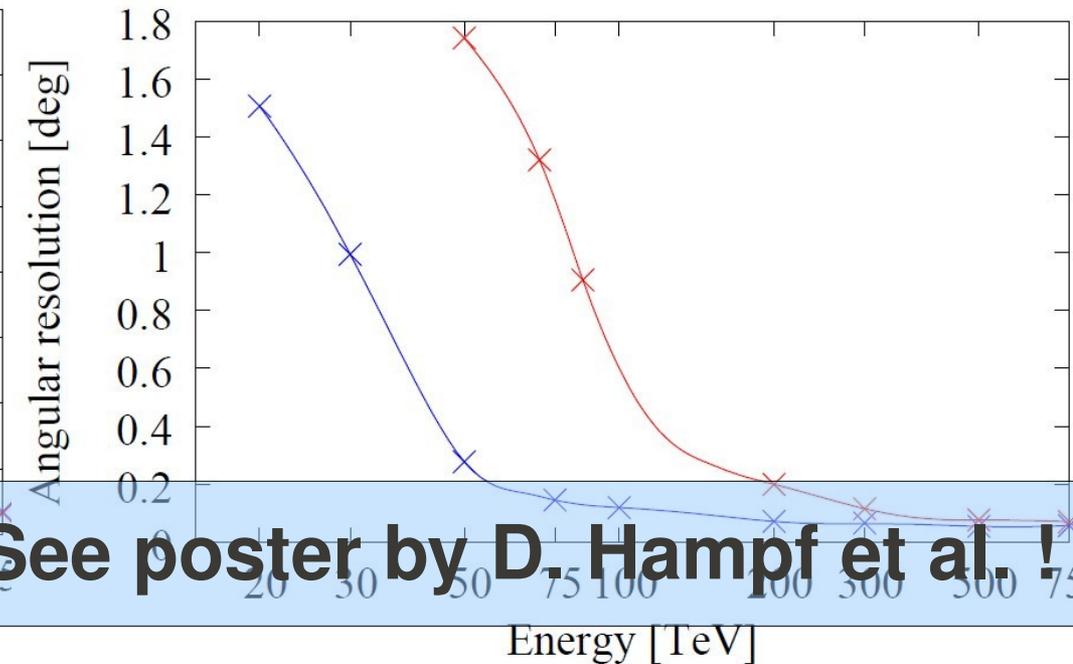
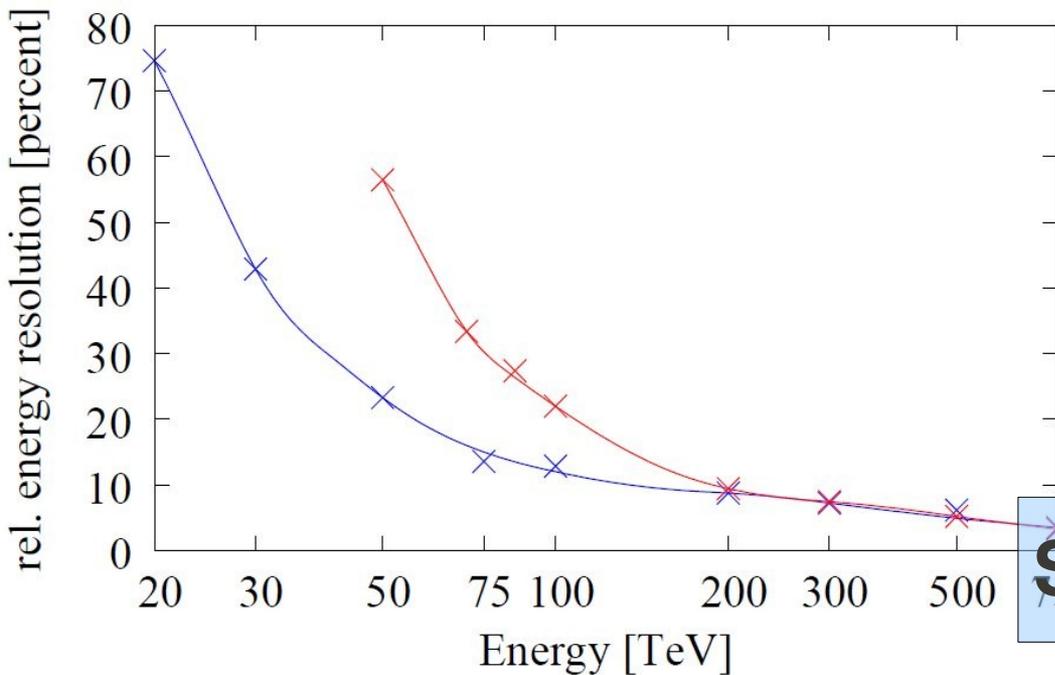
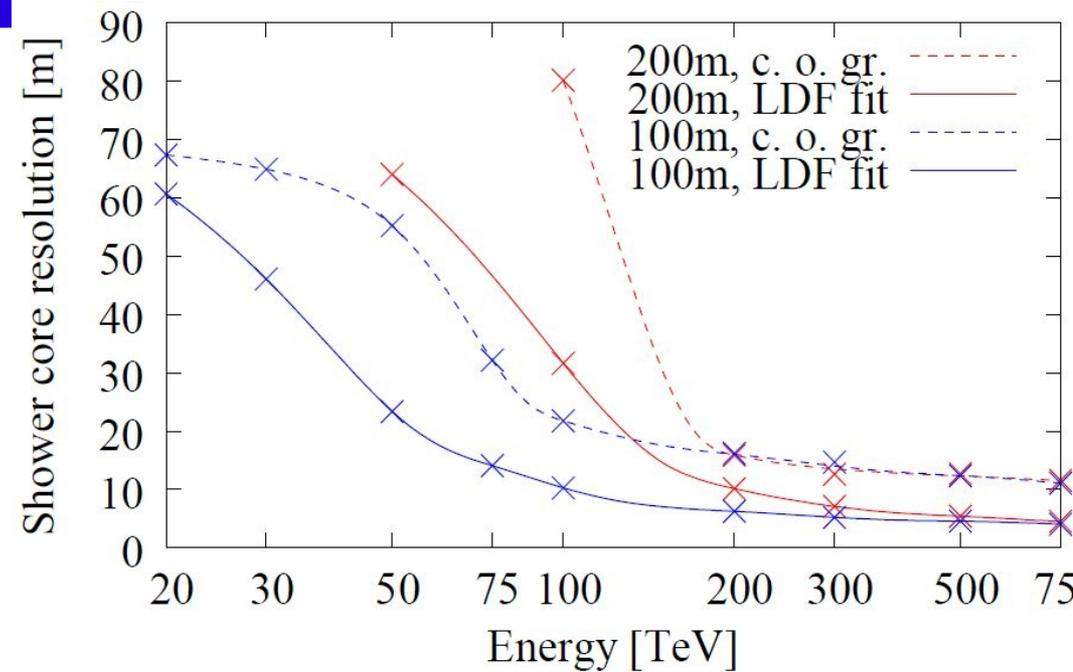
Trivial method: center-of-gravity of light distribution.
Improved method: 2D-fit of lateral density function to station data

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.



See poster by D. Hampf et al. !

Shower-depth

Shower-height reconstruction

1) timing:

Stack stations with same core distance: better S/N
Fit log-normal function to signal

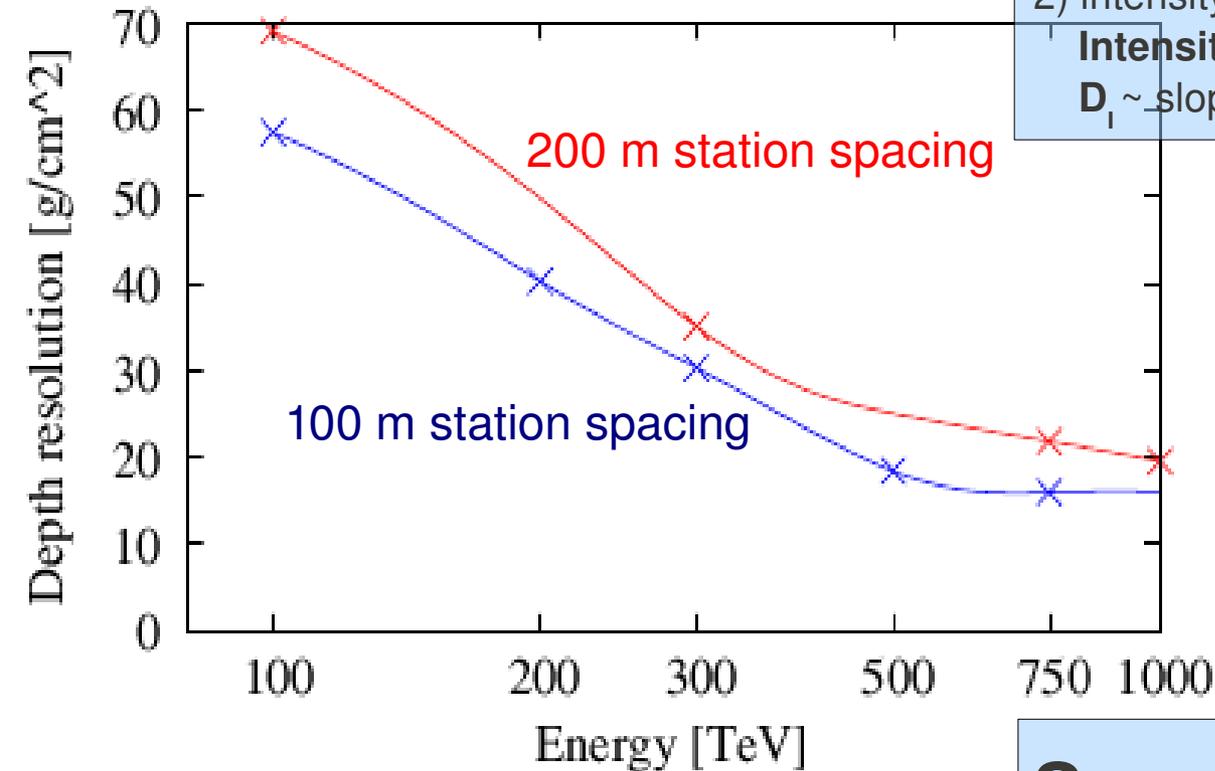
Width method, $D_w \sim \langle w \rangle = [w(300m) + w(400m)]/2$

Peak method, $D_p \sim a$ (from time peak fit: $a x^2 + b$)

2) intensity:

Intensity method,

$D_i \sim \text{slope of LDF}(50m) / \text{slope of LDF}(220m)$



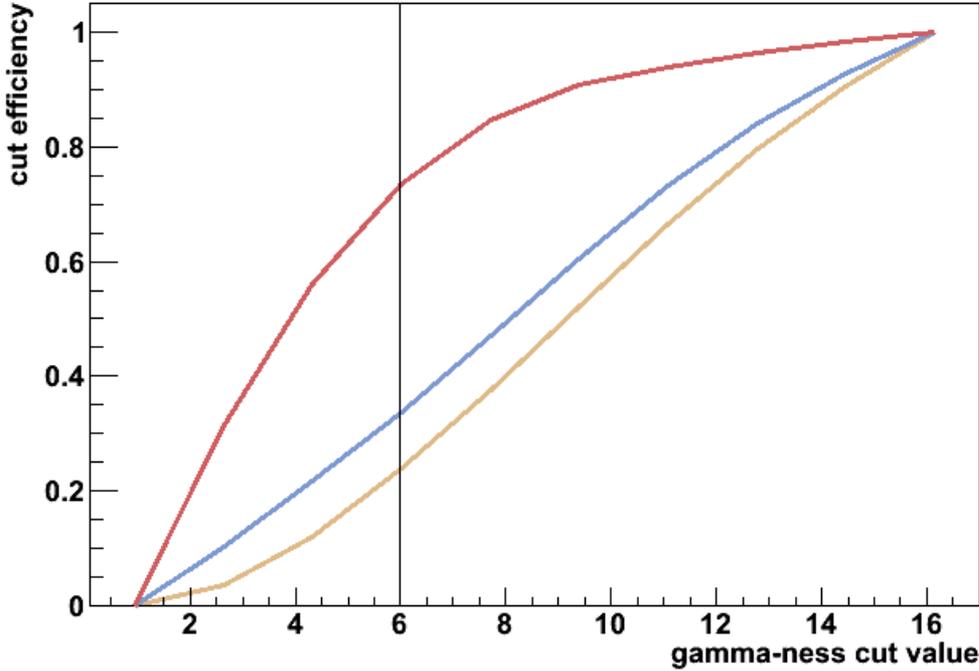
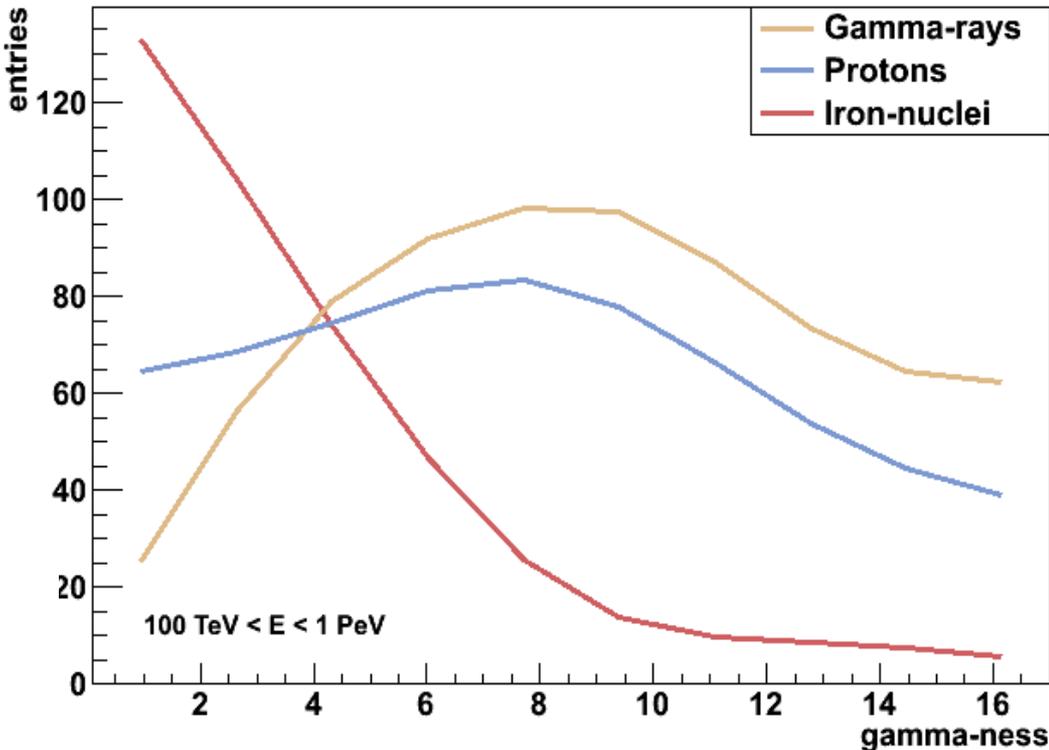
See poster by D. Hampf et al. !

Gamma-hadron & Particle separation

Gamma-hadron separation:

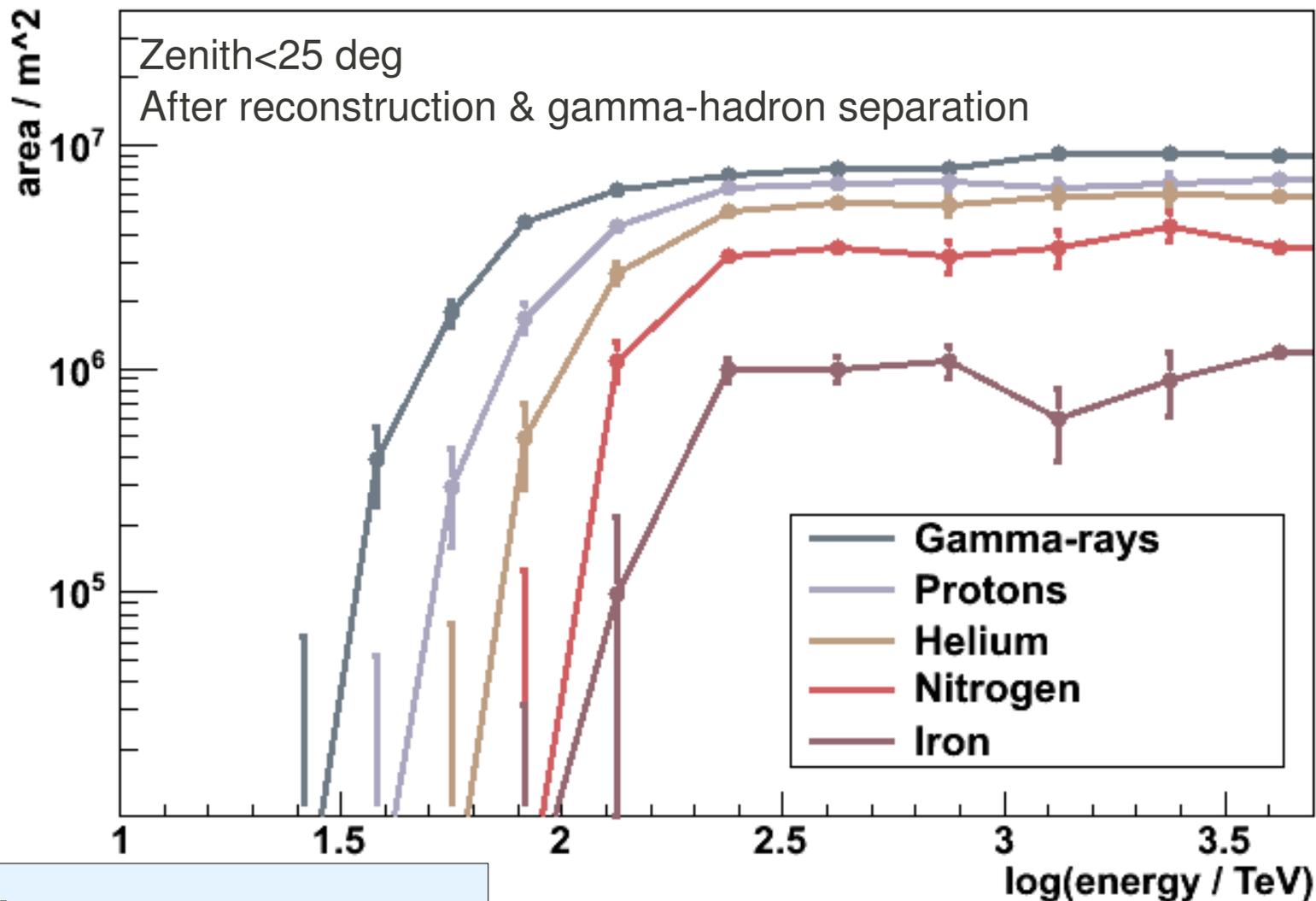
Differences in longitudinal shower development:
Shower depth / log10(energy)
Width / Shower depth

Higher light-concentration of gamma-showers: $N_{trg} / \Sigma A$



See poster by D. Hampf et al. !

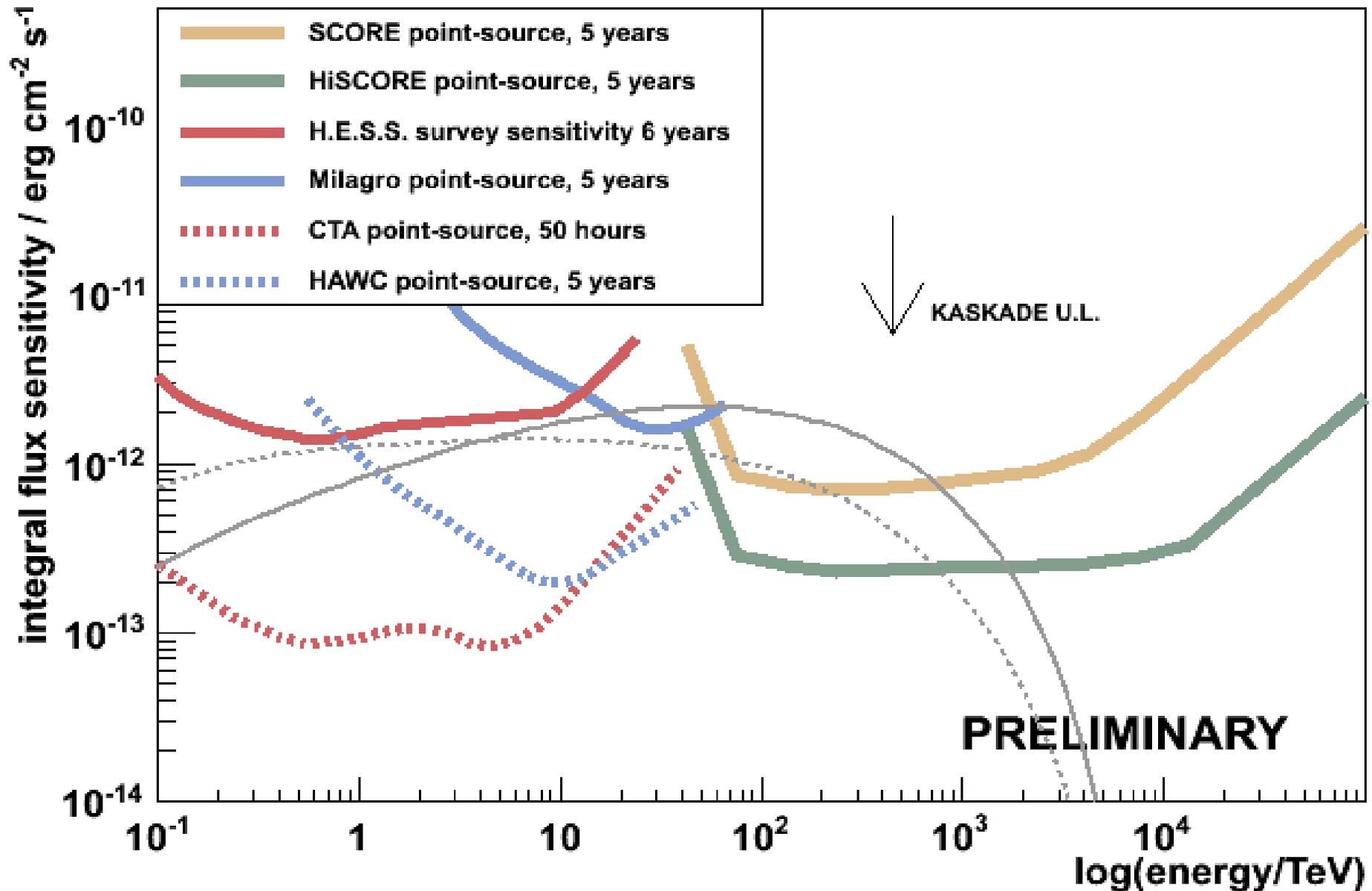
Effective area @ reconstruction level



Reconstruction cuts:

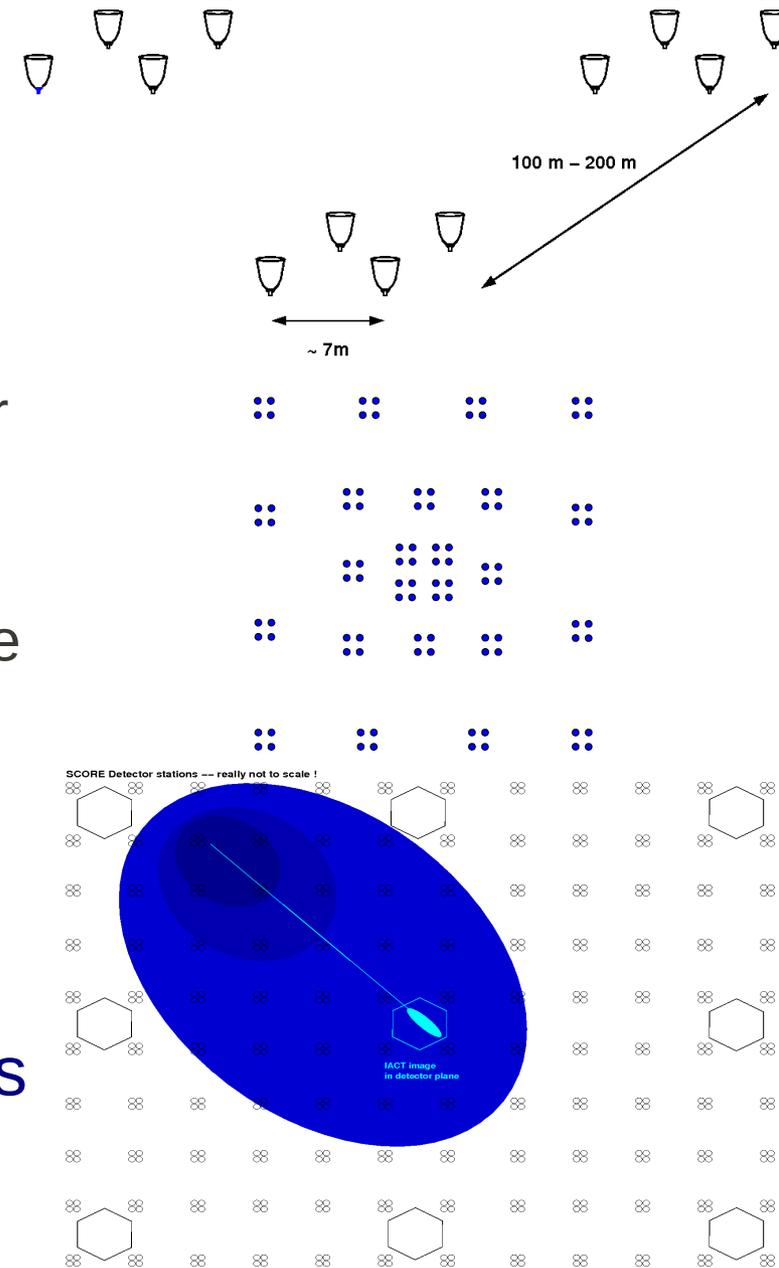
- ≥ 3 triggered stations
- Contained reconstructed core impact position
- Separator ≥ 6

SCORE Sensitivity



Status & current activities

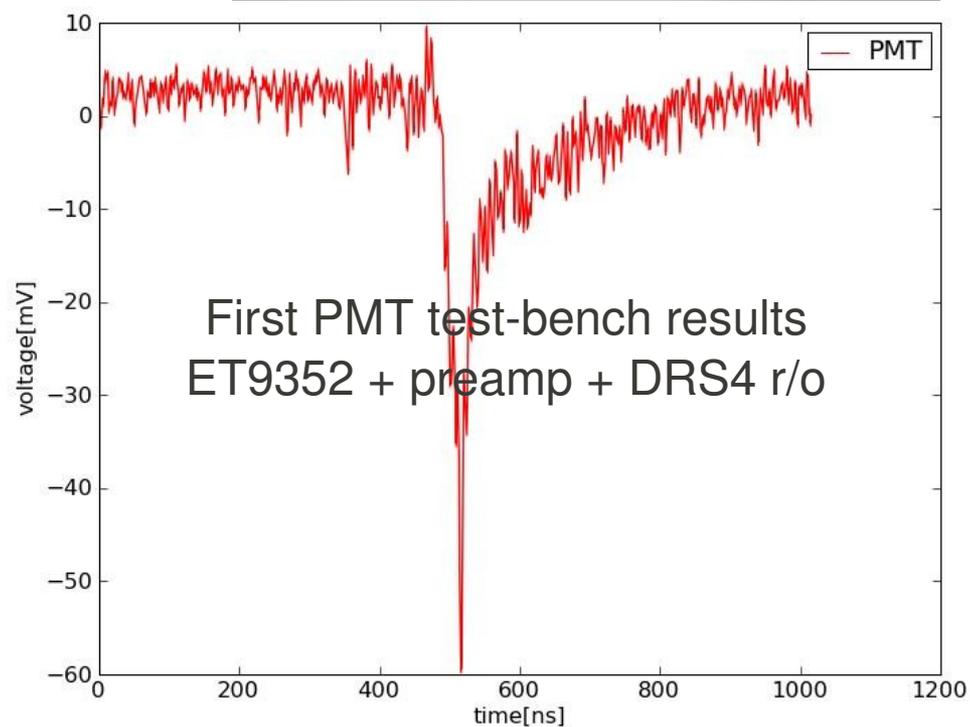
- Full detector simulation and basic reconstruction completed
- Improvements of layout:
 - **4-channel-cells, 7m X 7m:** Operate each channel independently 2-by-2 sub-arrays for better low-energy reconstruction
 - **Graded array:** decreasing station density towards array edge maximizes area for large energies
- Possible combination w/ IACTs e.g. CTA, TenTen
 - provide core to monoscopic telescopes
- Optimization of reconstruction algorithms (better understanding of shower-timing, e.g. V. Stamatescu, Poster)



Status & current activities

- Studies of first Hardware components in progress
 - Station mechanics
 - Winston cone
 - PMT test bed w/ 10 ET9352 PMTs
- Small-scale prototype in Hamburg (~4 stations)
- Planning large-scale prototype in Siberia: Engineering array
 - Plan cooperation with Tunka group, MSU Russia
 - Planning construction of **~0.5 km² array in Siberia**
 - Synergies with Tunka-array (see M. Panasyuk, E18-0033-10), radio detectors and planned Tunka μ -detector
 - Preparing order for further ~100 PMTs

Status & current activities



Roadmap

Engineering array ~ 2010 – 2012

SCORE: Study for a Cosmic ORigin Explorer

Site search, deployment on ~10 km²

2012-2014

HiSCORE: extend SCORE to few 100 km²

Summary

Many physics cases beyond 10 TeV primary energy

The sensitivity goal is already **reached by SCORE**

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

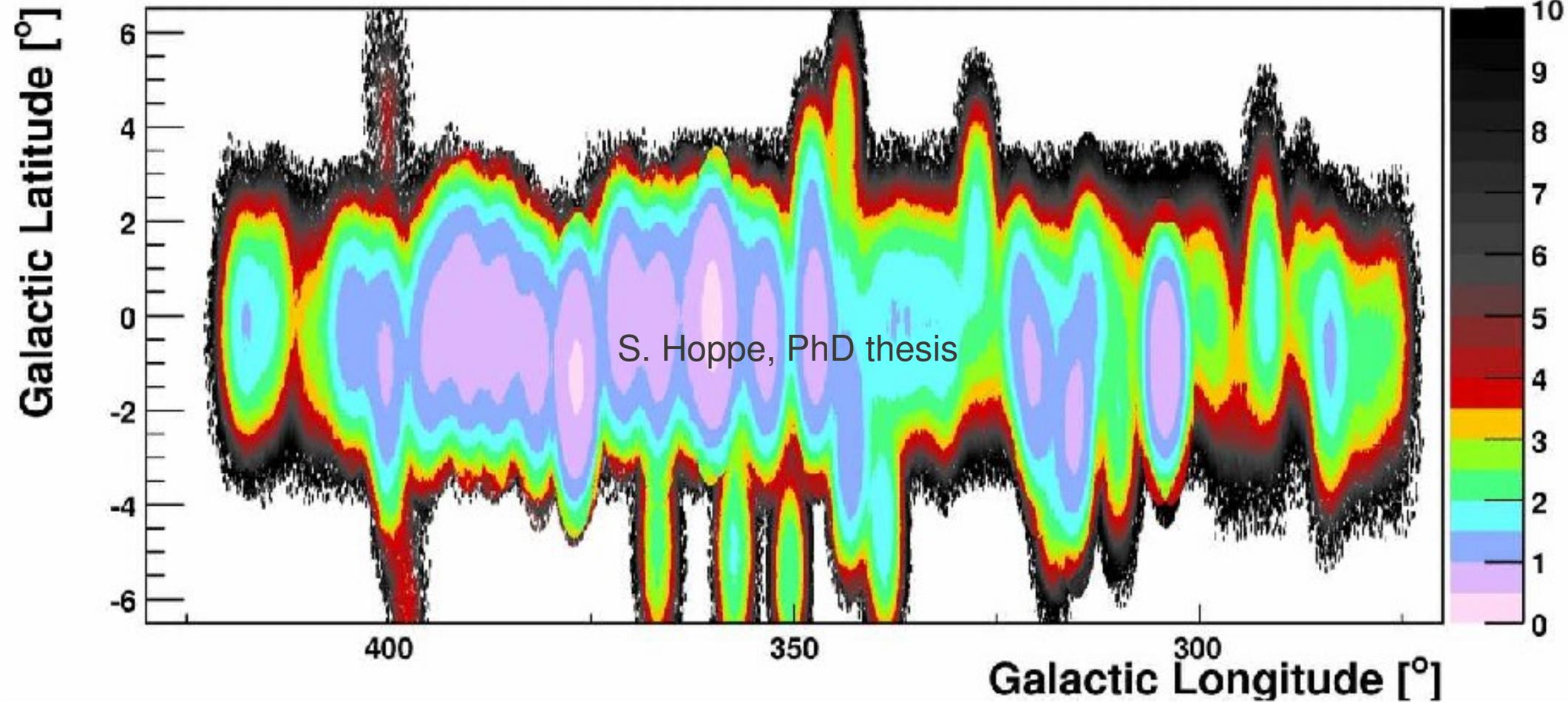
Cooperation is welcome

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)
- [Shibata et al. 2010] M. Shibata, Y. Katayose, J. Huang and D. Chen, ApJ 716, 1076 (2010)
- [Blümer et al. 2009] Blümer, Engel & Hörandel Progr. in Part. and Nucl. Phys., 63/2, p 293 2009

Backup

H.E.S.S. survey sensitivity



Expected pevatron signal

Assuming MGRO 2019+37 is a pevatron
(1deg extension, $3.49 \cdot 10^{-12} \text{ TeV cm}^{-2} \text{ s}^{-1} @ 12 \text{ TeV}$)

$$dN/dE = 4.26 \cdot 10^{-8} (E/\text{TeV})^{-2} e^{-\text{sqrt}(x/300\text{TeV})} [\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}]$$

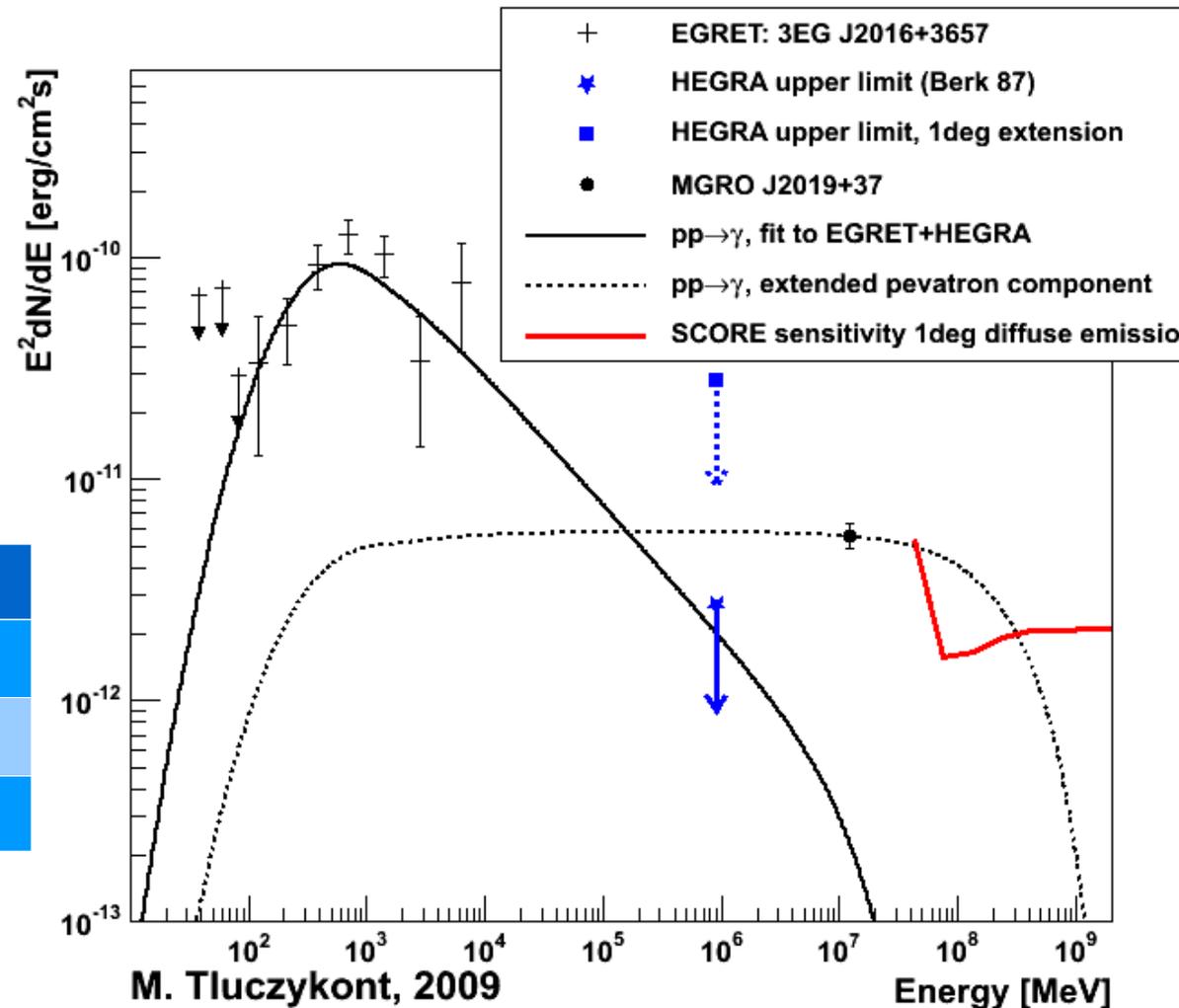
Fold dN/dE and Hörandel
w/ post-reconstruction area

Integral event numbers

2deg source region

5 years observation time

Energy	gammas	hadrons	Signific.
>50 TeV	7000	1050000	6.8
>100 TeV	4000	450000	5.9
>1PeV	100	20000	0.7



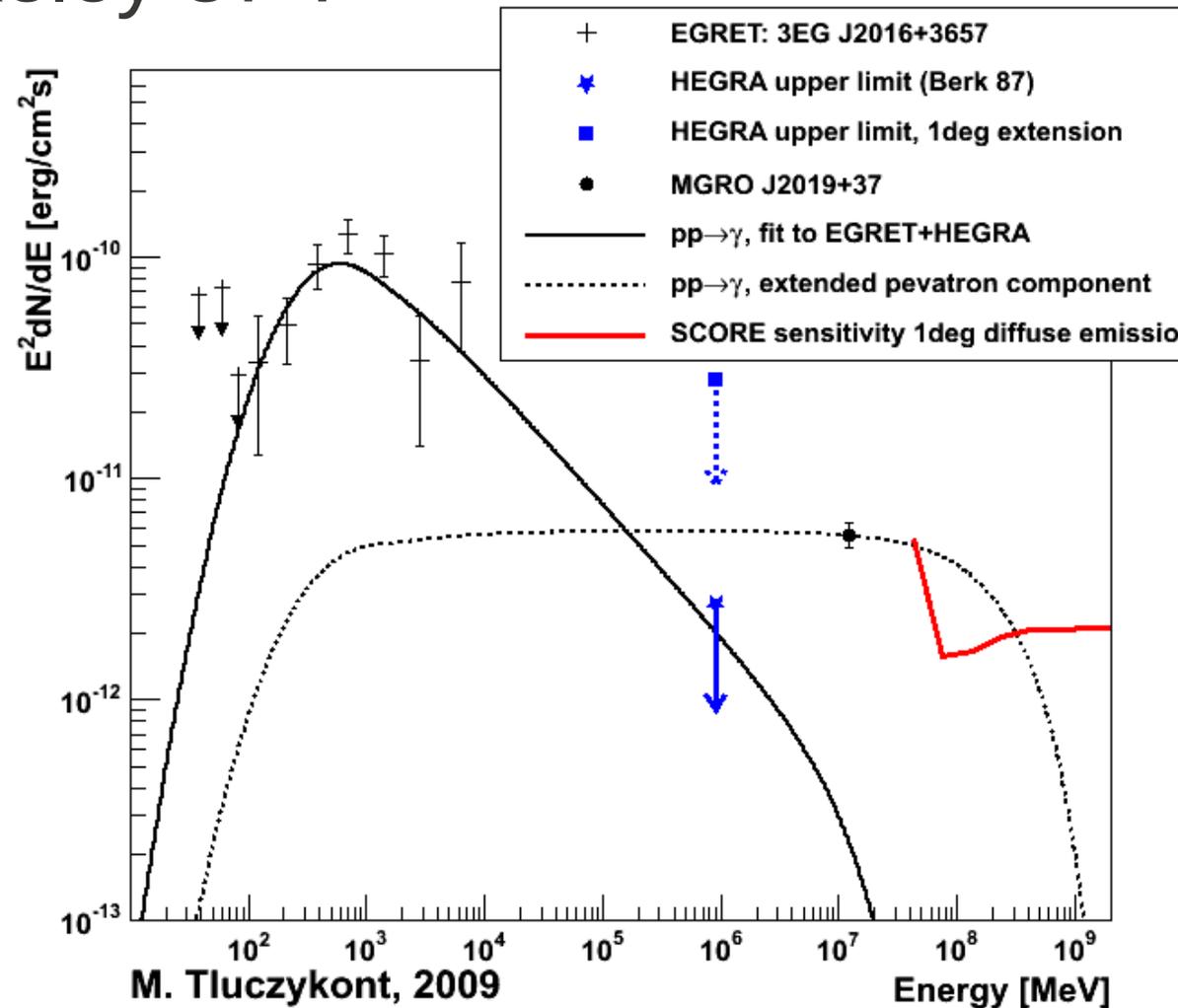
Pevatron emission from Cygnus ?

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

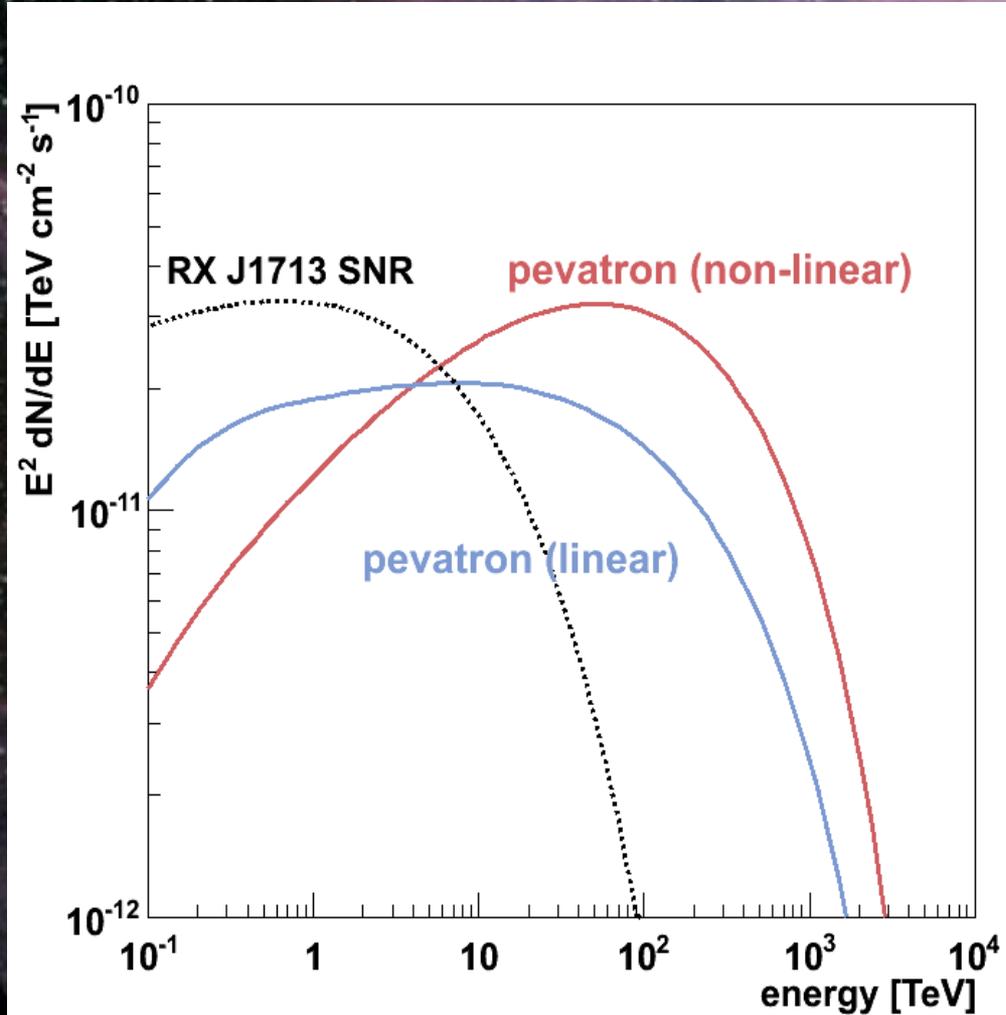


Milagro signal might be dominated by extended pevatron emission !

SCORE: resolve emission from 10 TeV – 1 PeV

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 !

p-p cross-section

Correlation shower depth / first interaction
→ measure interaction length in air $\sigma(\text{p-p})$

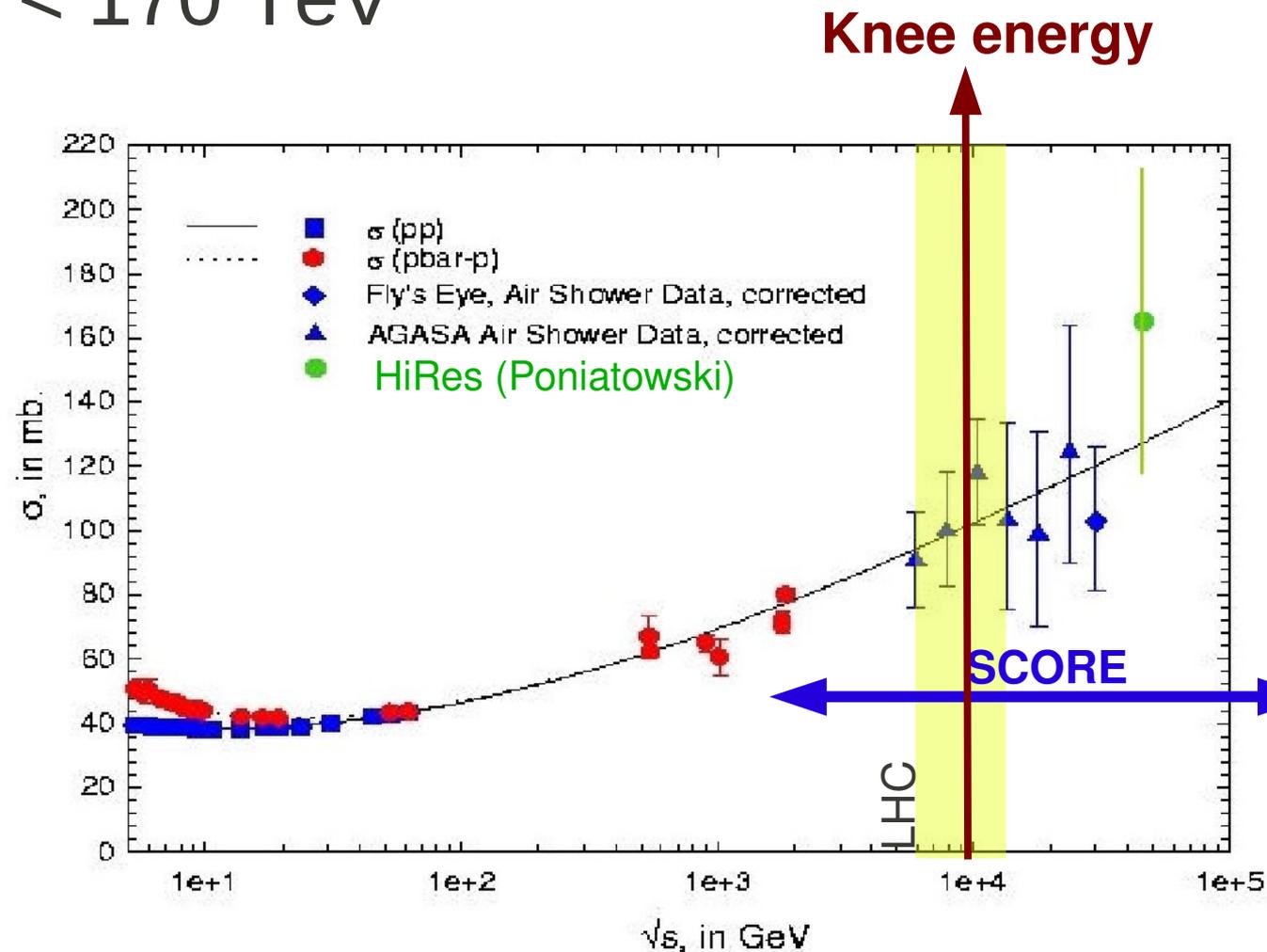
SCORE: $1.7 < E_{CM} < 170 \text{ TeV}$

Particle physics-
origin of knee ?

Overlap:

LHC

CR experiments



Propagation: Galactic Absorption & CMB

e^+e^- pair production: Interstellar radiation field (ISRF) and CMB

estimate ISRF density

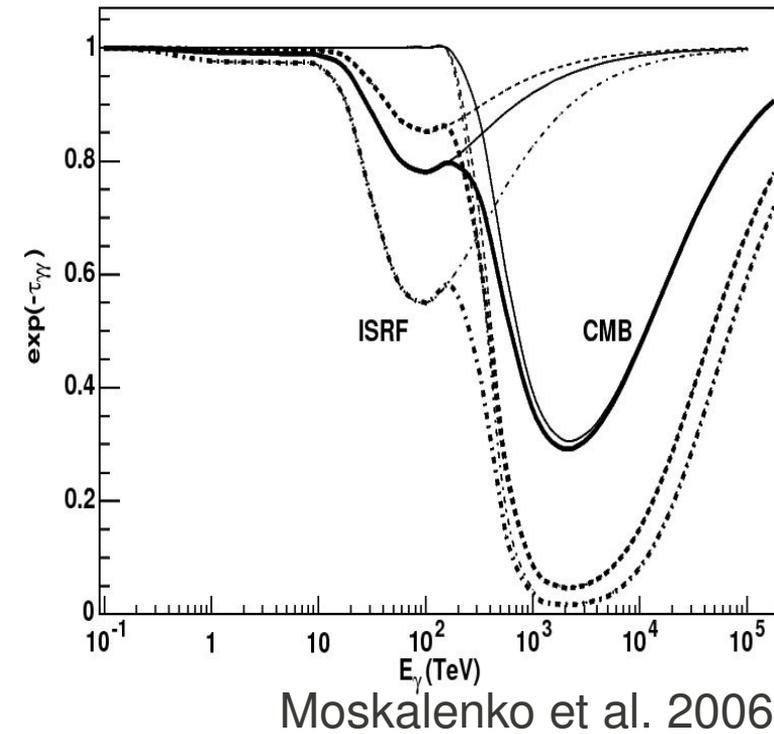
CMB well known: **distance estimate?**

Weakening of absorption by:

Photon / axion conversion in Galactic Magnetic field

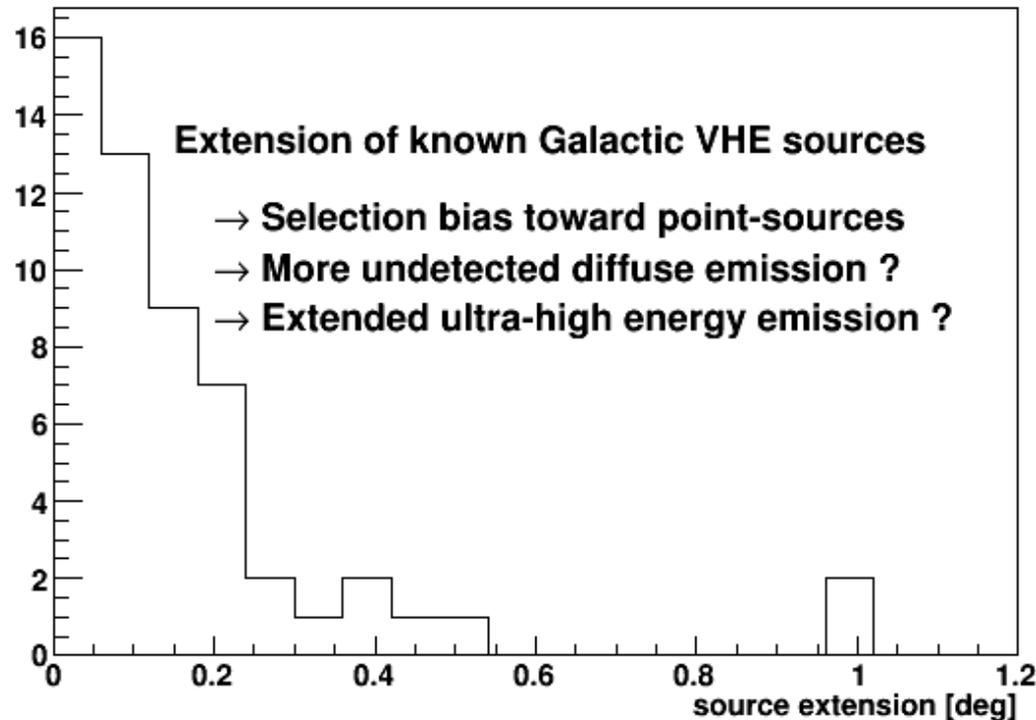
Photon / hidden photon oscillation

Lorentz invariance violation (modification of e^+e^- threshold)



Moskalenko et al. 2006

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**

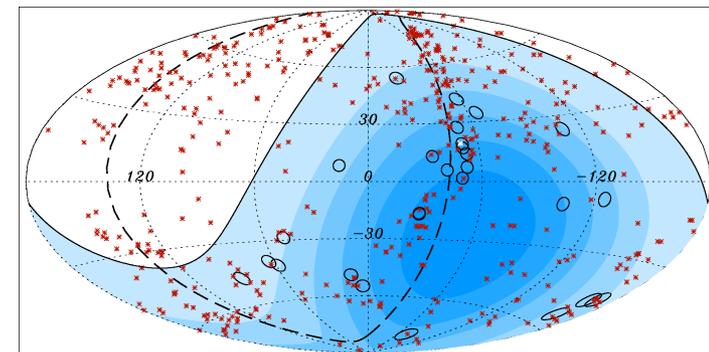
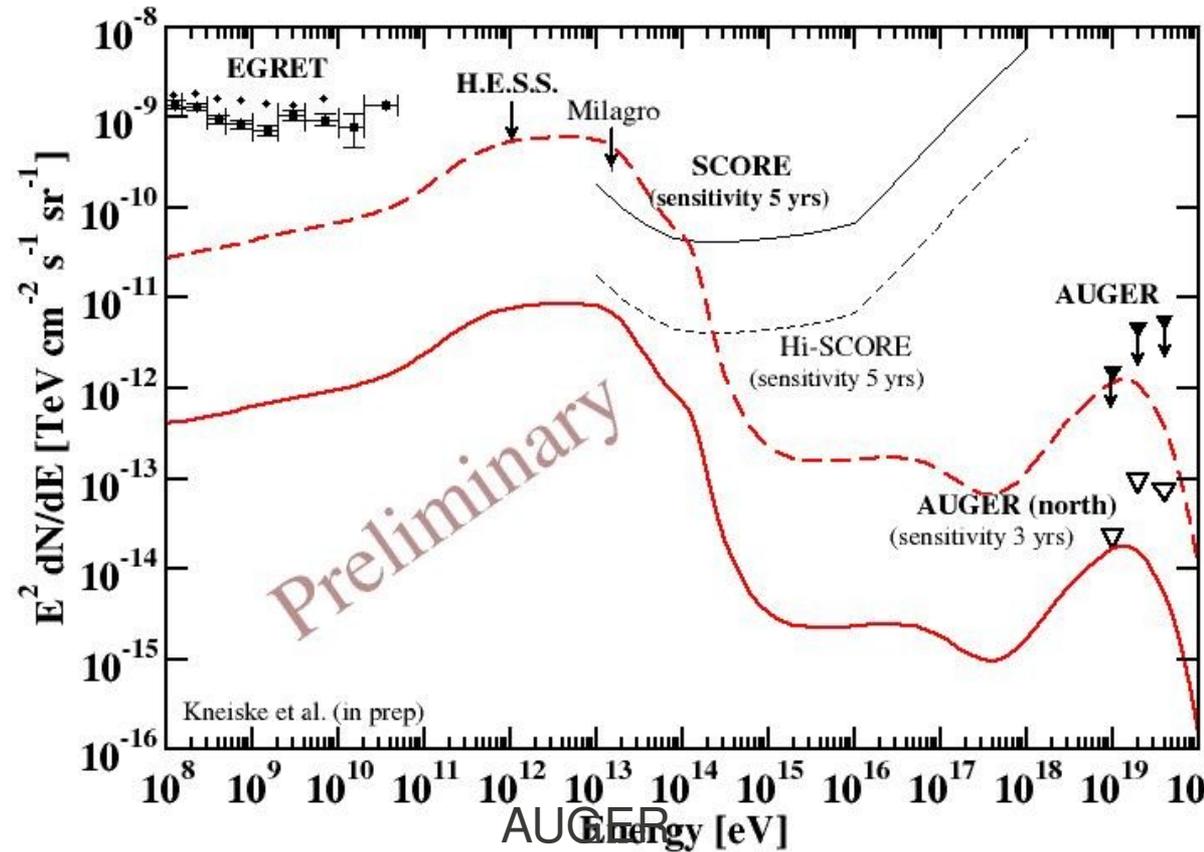
Expect diffuse emission

See *T. Kneiske, Lodz 2009*

Point-sources from AGN ?

IC Pair-cascading

Haloes ?



Monopoles

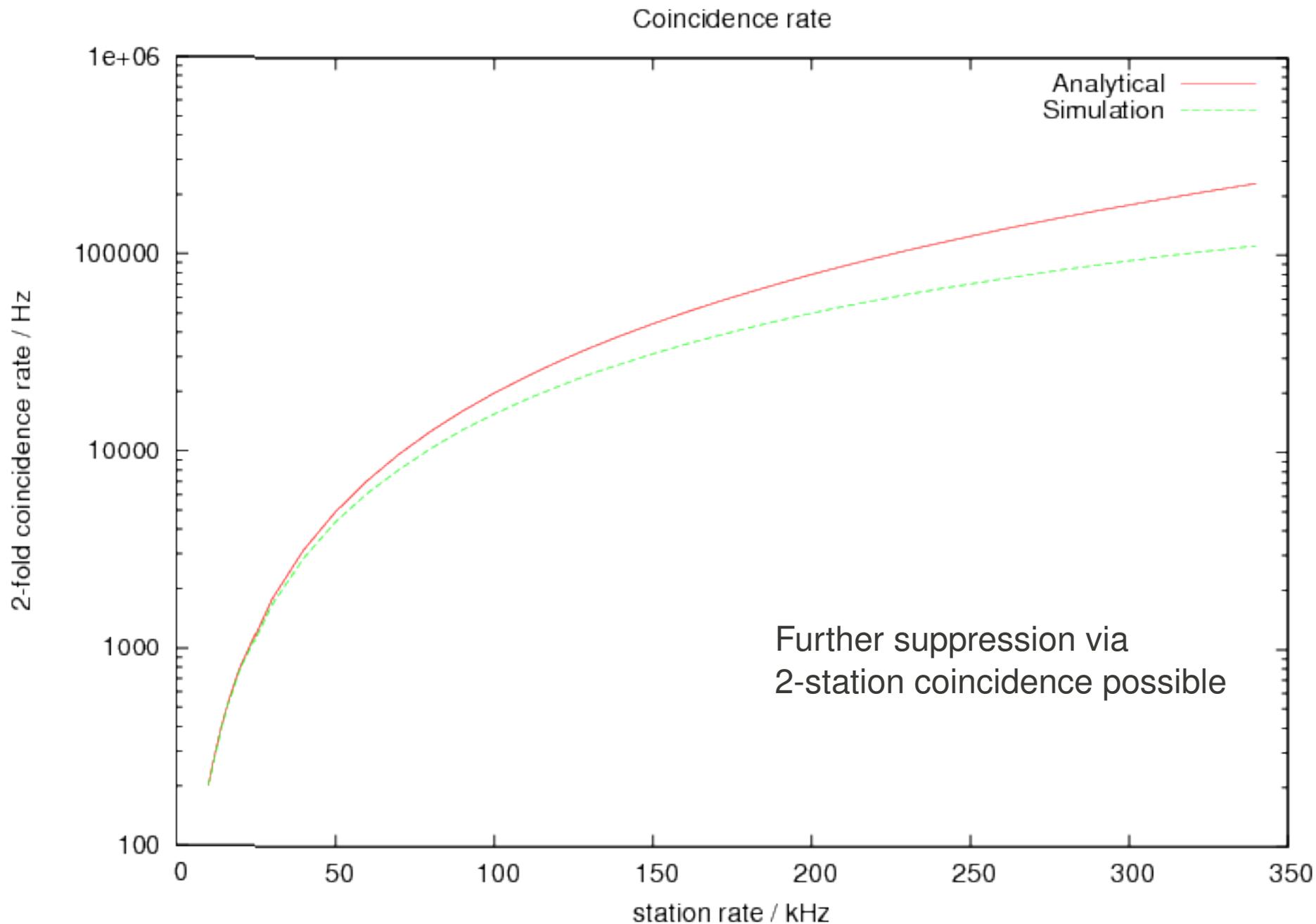
Monopoles emit a lot of Cherenkov light

Study by Gerrit Spengler (Berlin): Monopole search with H.E.S.S.

Might reach AMANDA sensitivity with CTA

Even better with SCORE ?

Expected night-sky background trigger rate



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

NSB rate: La Palma (Mirzoyan & Lorentz 1994, MPI-PhE/94-35)

Random photons equally distributed in time

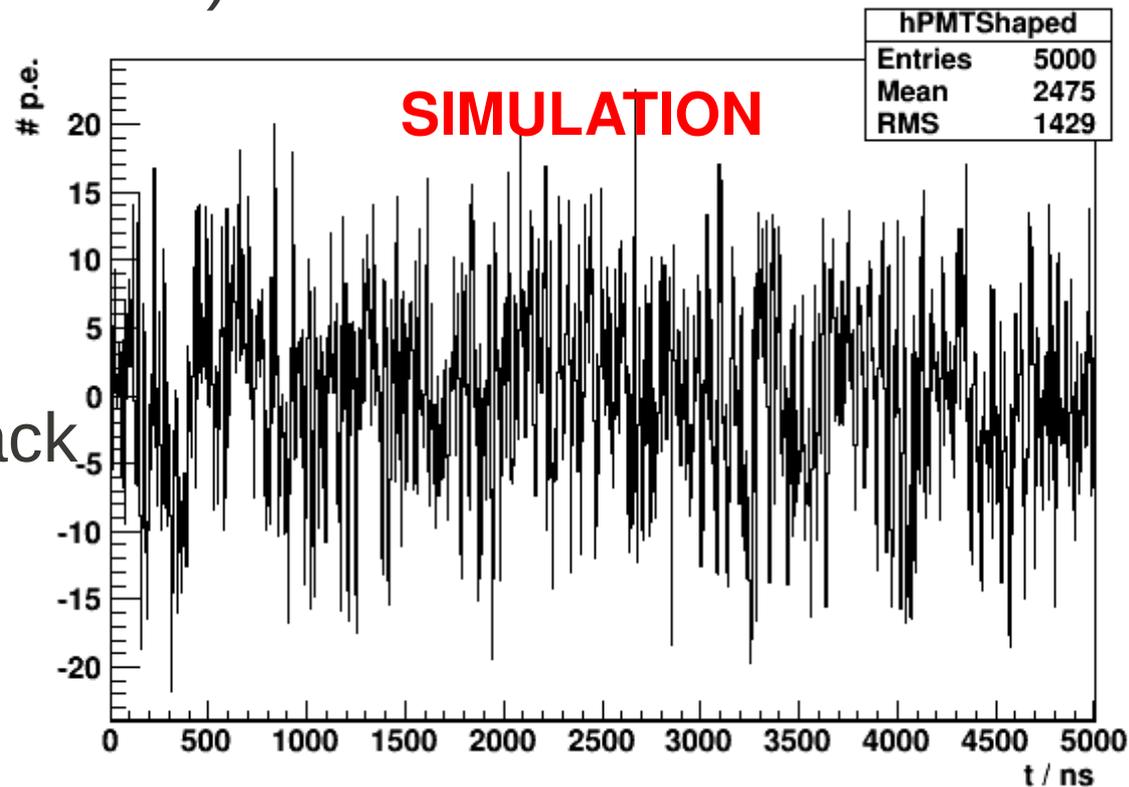
Simulate 4 modules with Pulse shaping: “Henke” shape

Simulate 4 discriminators (width 20ns)

Require local 4-coincidence

01/09/2009 – 28/02/2009:

NSB measurement in outback
(D. Hampf)



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

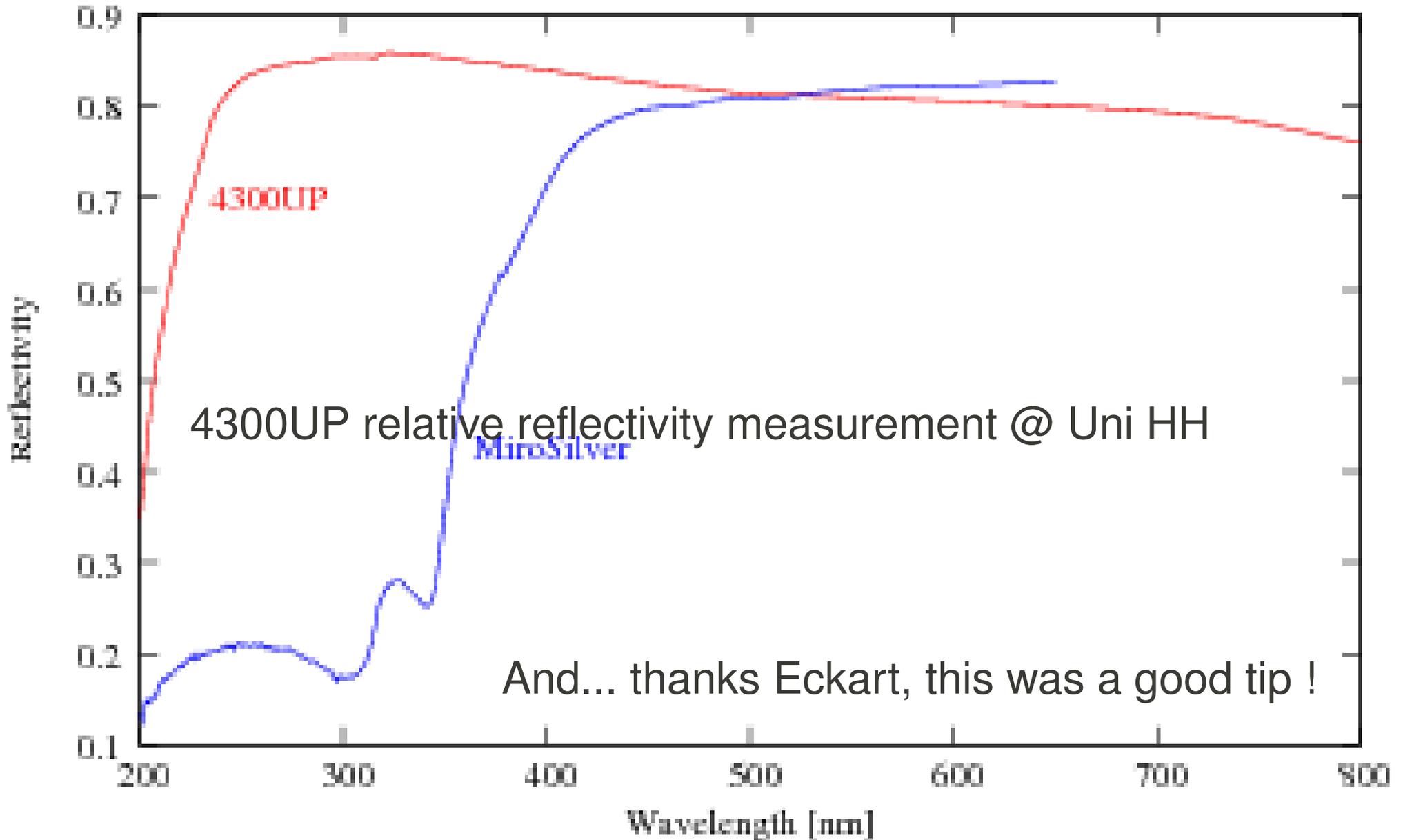
Planning first prototype deployment on DESY site:

⇒ closed stations w/ scintillator, for **testing electronics**

NSB measurement in Australia

⇒ RP580 PMTs, discriminator + ADC/scaler for NSB photon count

Hardware Prototyping / Testing



Funding

Existing funds of Group of Prof. Horns:

⇒ hardware prototyping (SCORE, CTA)

Waiting for reply from DFG:

⇒ *“Initiation and intensivation 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)

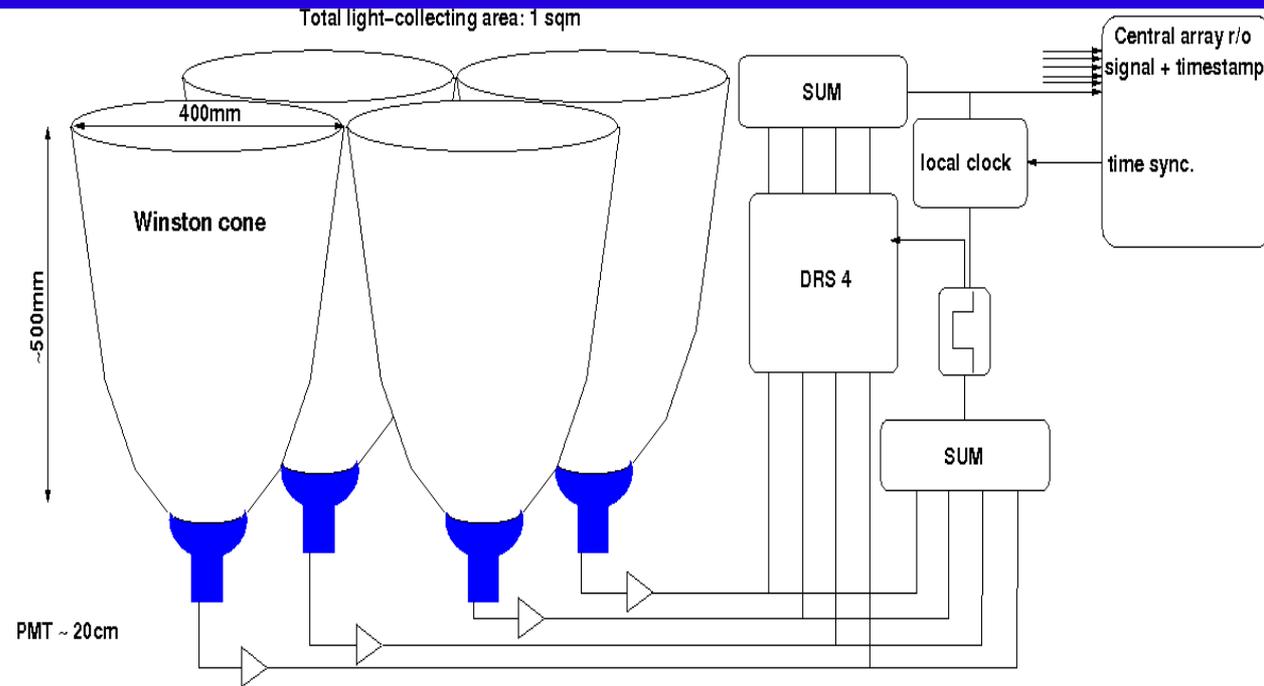
Envisaged:

Application to BMBF (?)

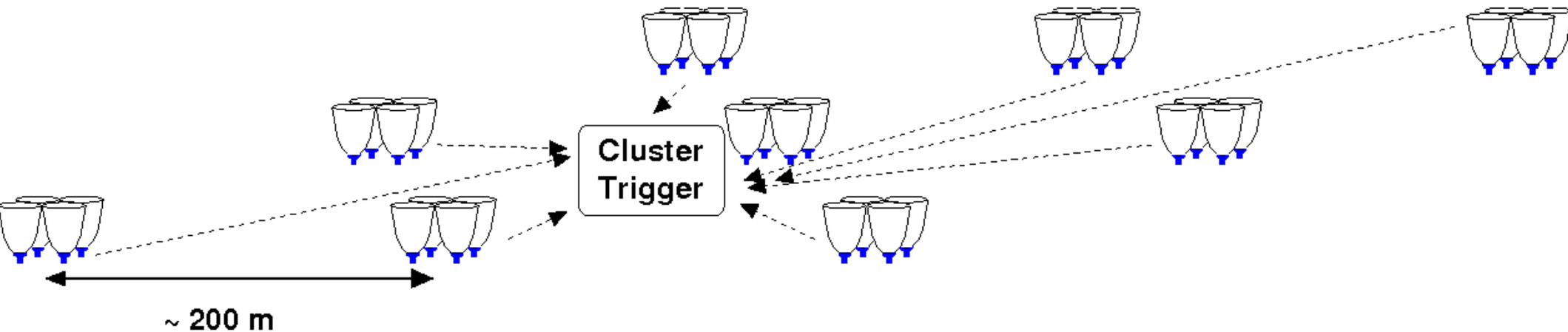
Application for EU Instrumentation / Infrastructure

Trigger levels

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



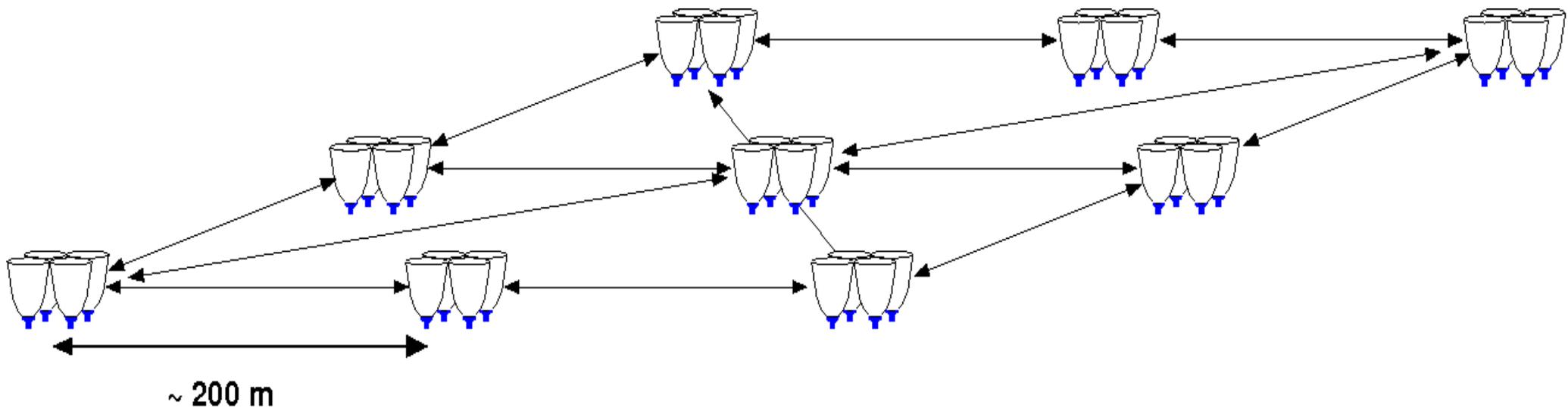
Array trigger: next-neighbour station trigger ($\Delta t = 1\mu\text{s}$)



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 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”

GPS is no option: 10 ns

And central synchronization time T_s

Optical fibers: expensive

Station switches to “wait for sync”

Alternative: Lightsource synchronization:

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

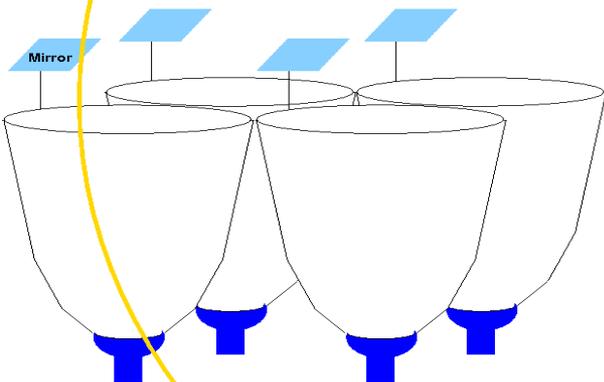
Isotropic lightsource at central array readout

Station triggered by light pulse

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

Small mirrors on each cone: deflect light on PMT

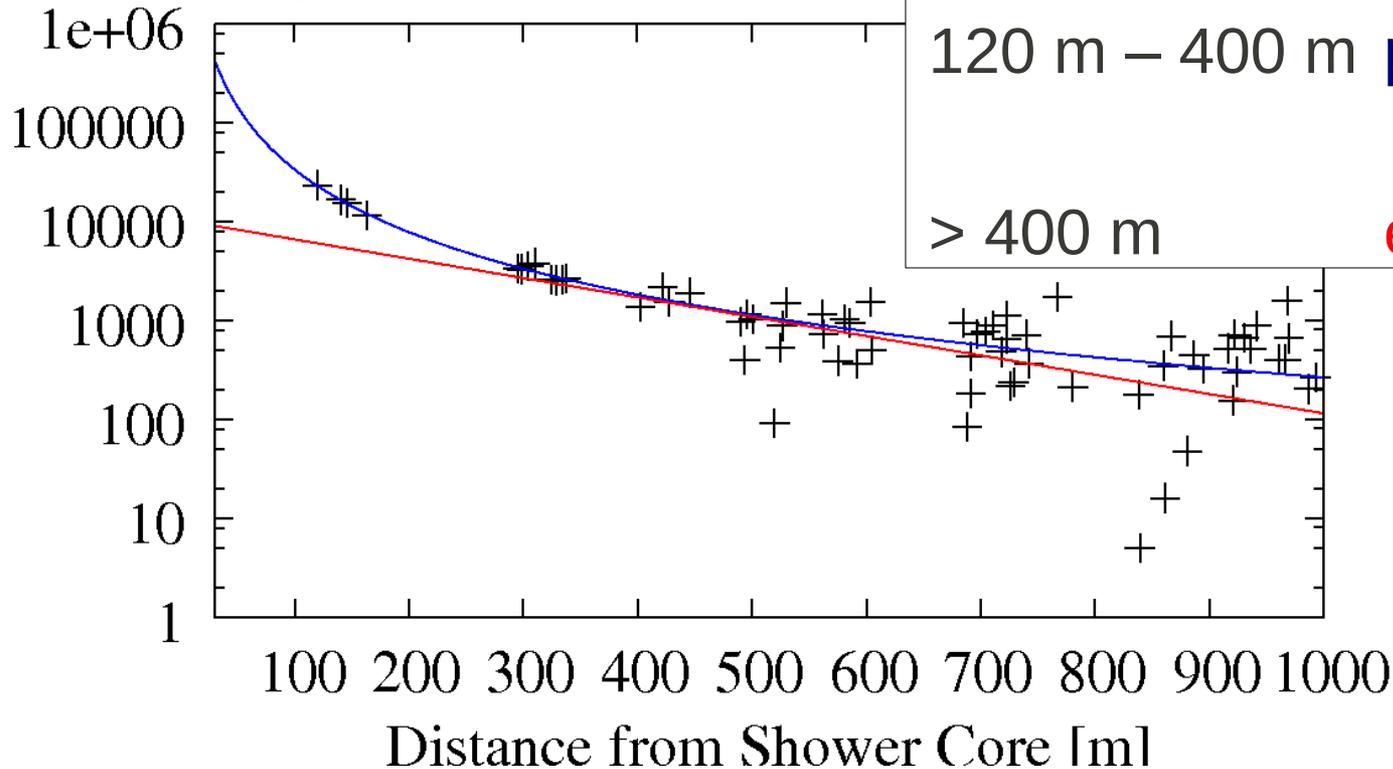
Dead-time: 10ns + synchronization length



Lightsource

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 !

Shower Depth

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

Timing methods:

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

Fit log-normal function to signal

Signal width:

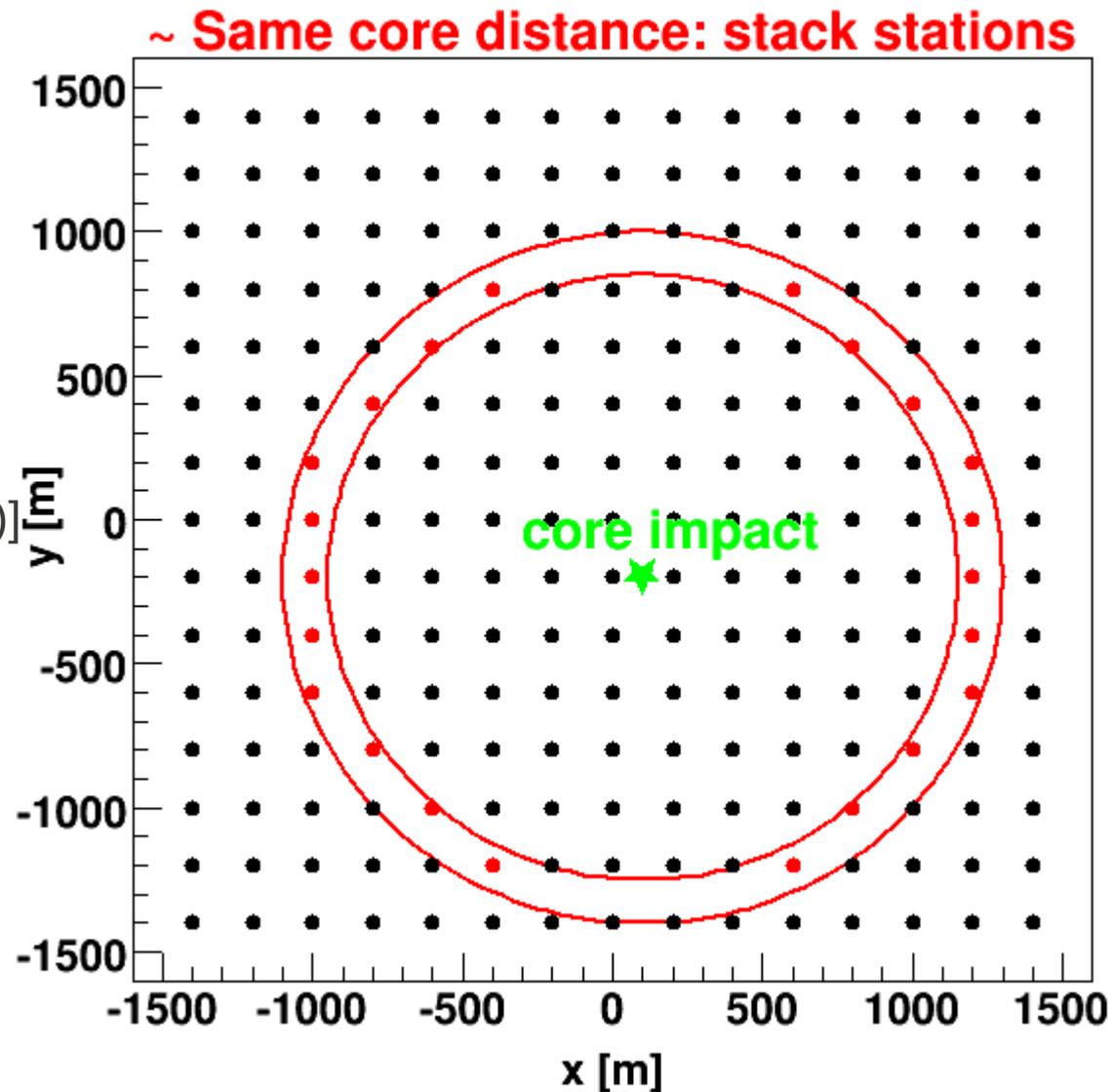
depth $\sim \langle w \rangle$

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

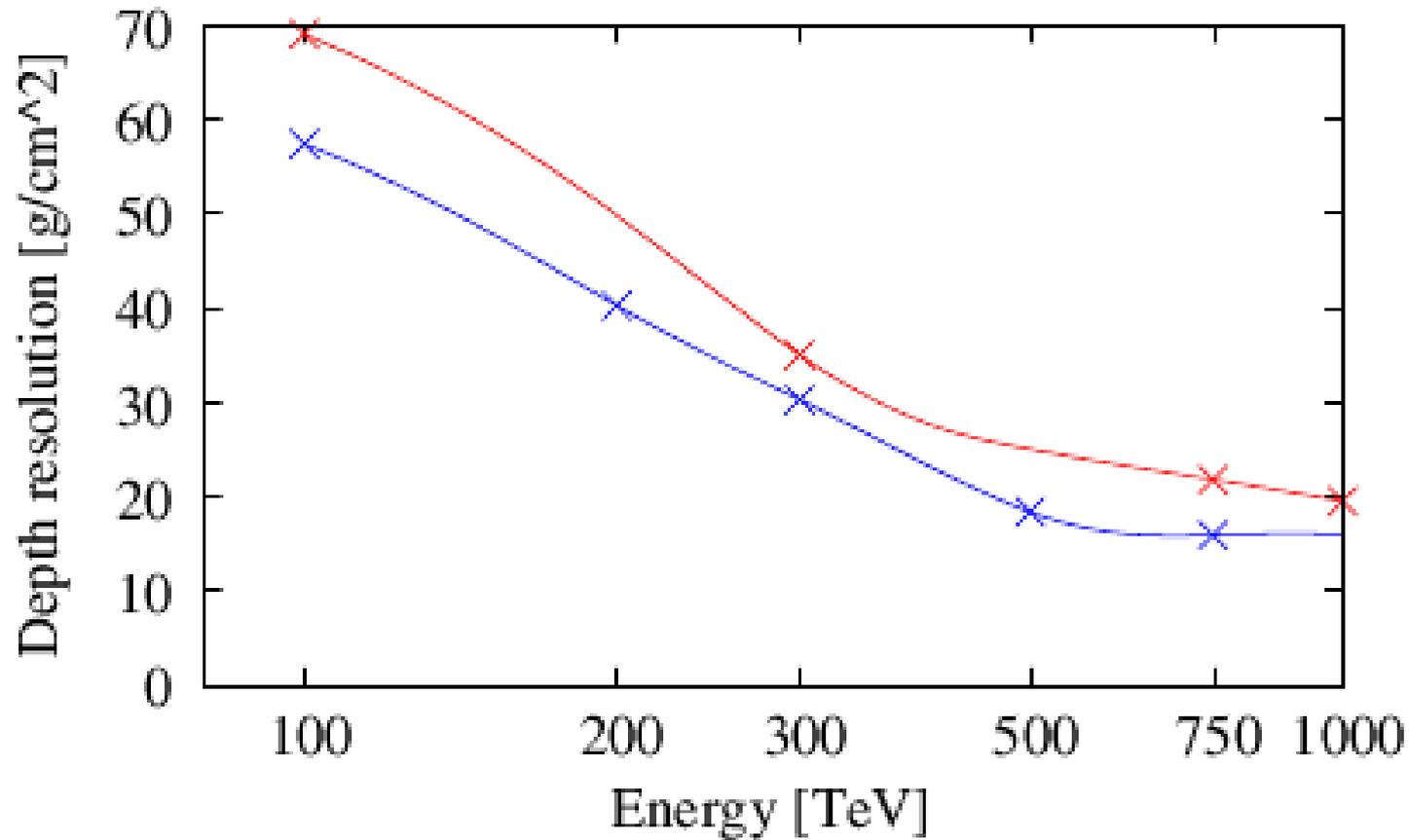
Signal peak:

depth $\sim a$

(from time peak fit: $a x^2 + b$)



Shower Depth

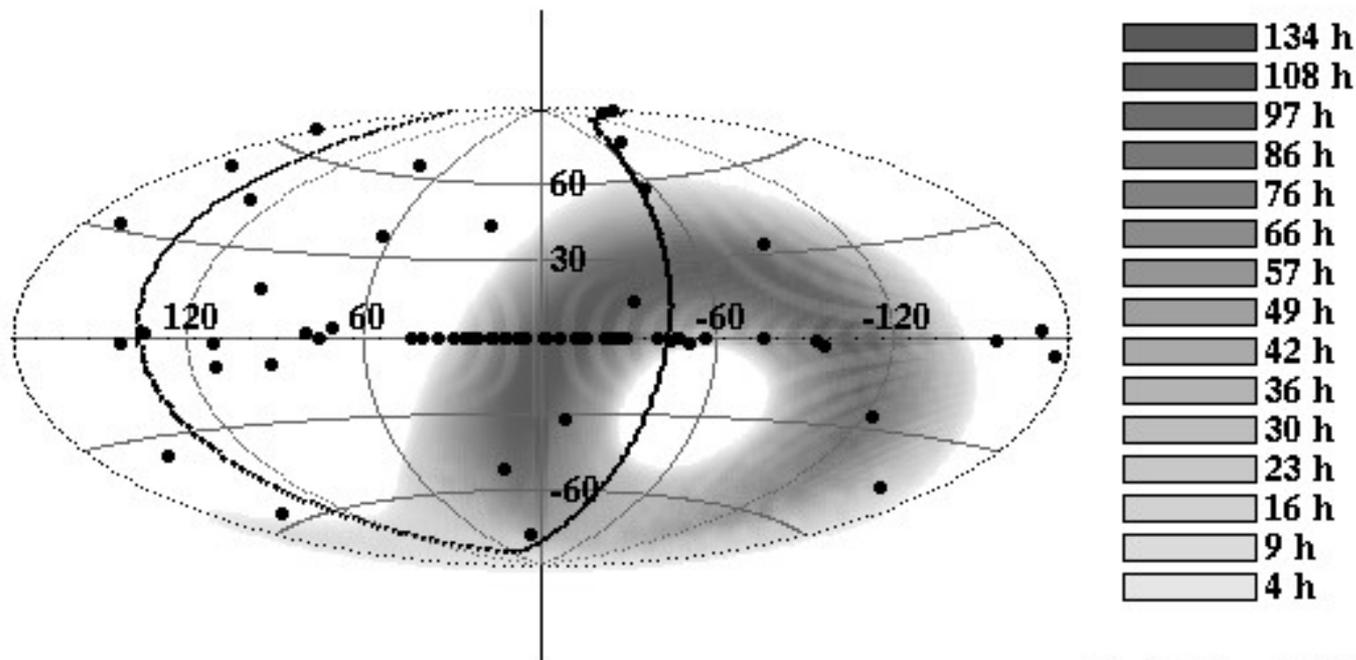


Exposure in Australia

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

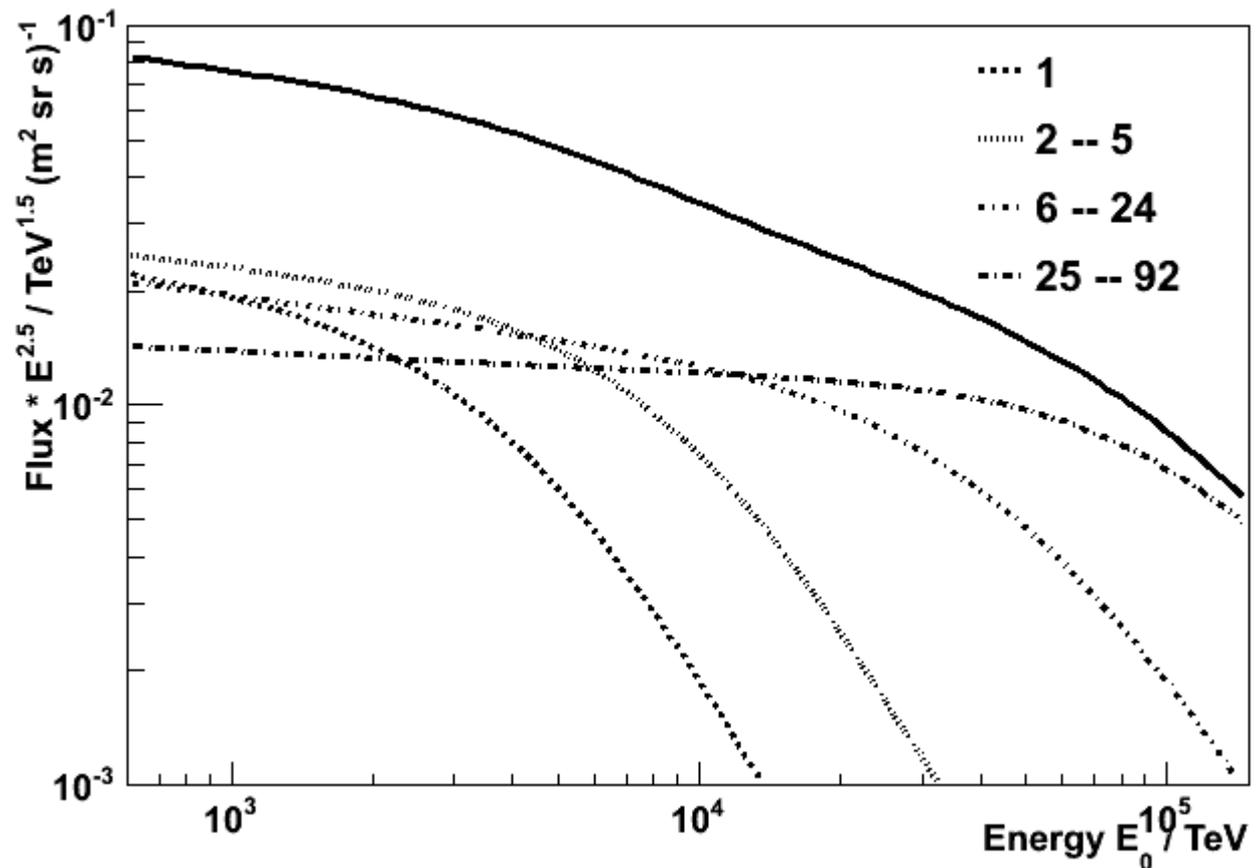
Hoerandel 2003: polygonato model

Hadron rates for SCORE, 10 m², 0.85 sr (theoretical rates):

$E > 10$ TeV: 25 kHz

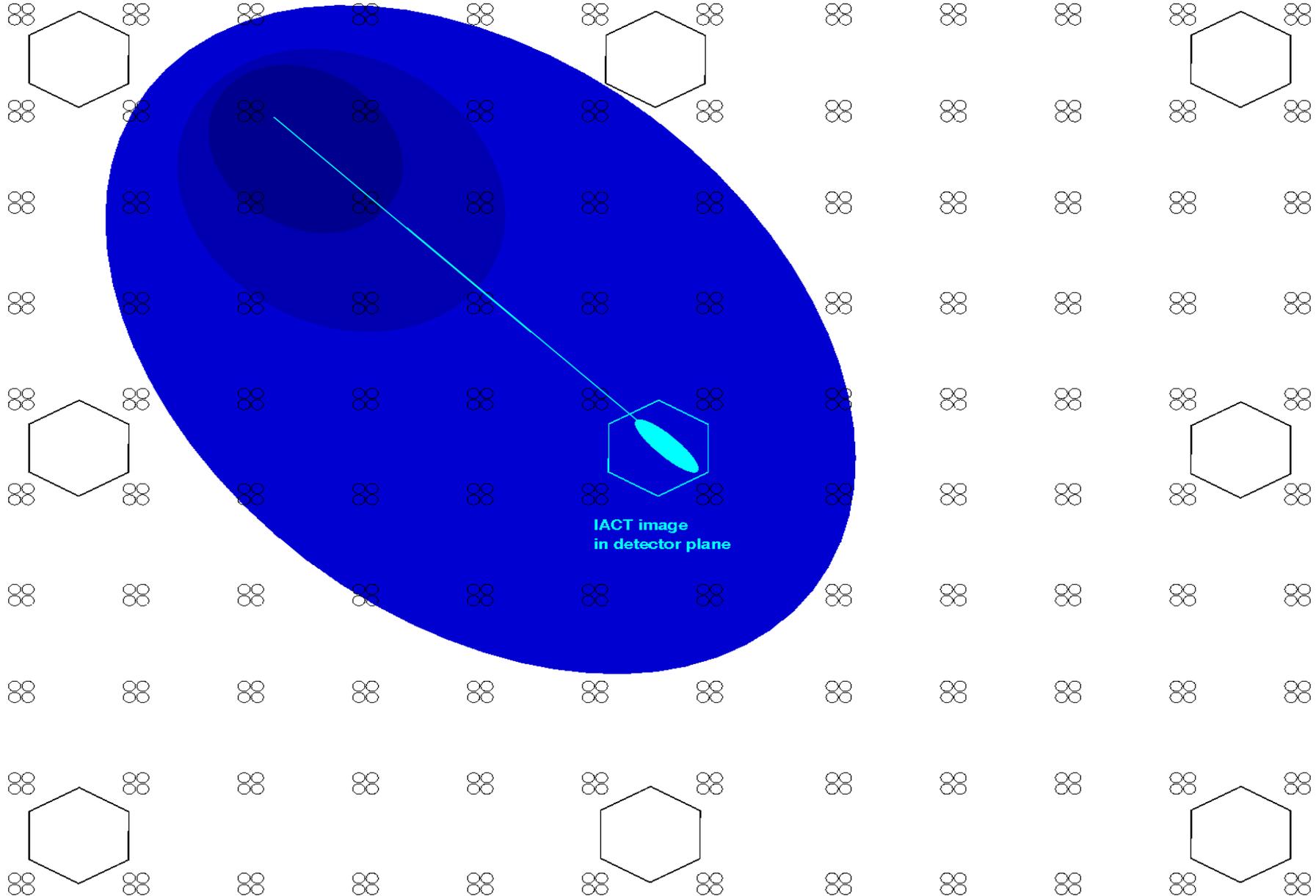
$E > 100$ TeV: 500 Hz

$E > 1$ PeV: 10 Hz



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_{eff} / channel ratio !**

Caveat: observations constrained to station viewcone (overcome this with station steering ...)

Working on ... testing this in simulation

Alternatives / Extensions

Daytime-measurements with scintillator material
in lid: 100% duty cycle

Combination with imaging technique:

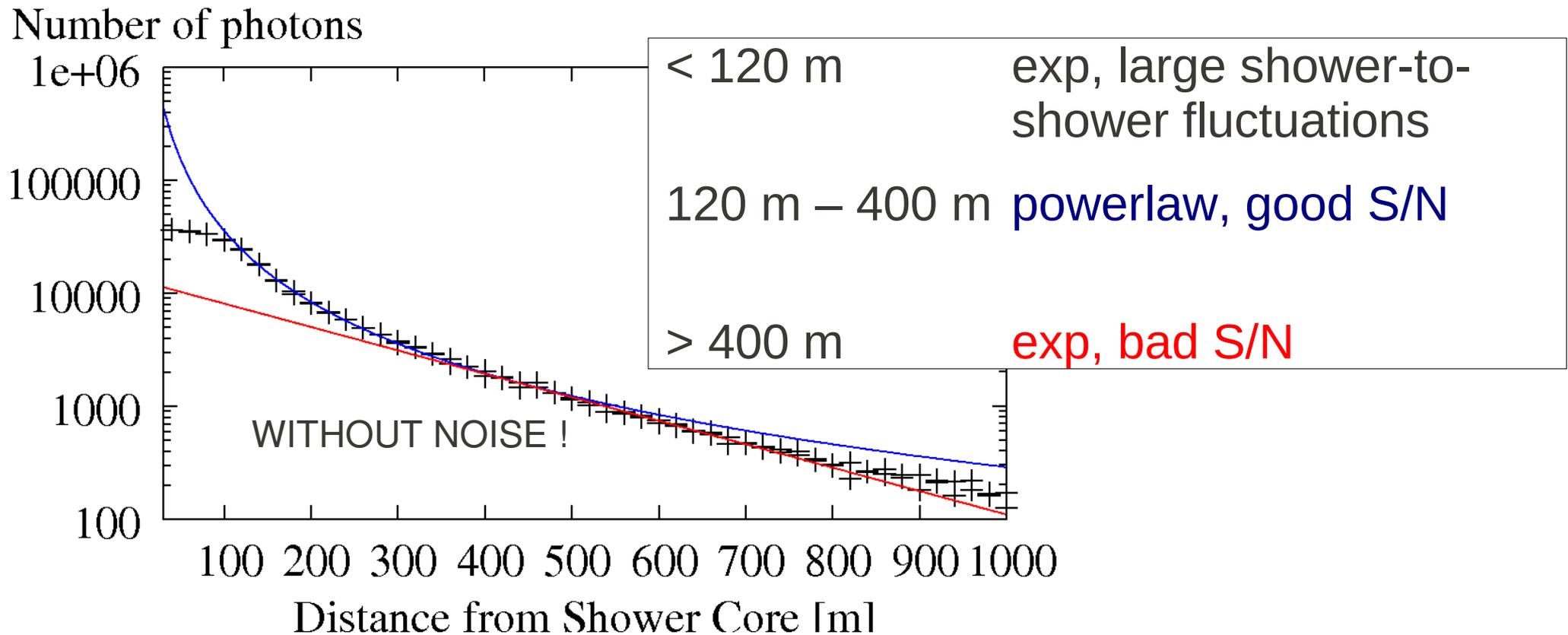
provide core-reconstruction for low-density telescope grid
(even monoscopic ?)

Instrumentation of larger area for highest energies

Combination with radio detection technique ?

...

Amplitude: The Lateral Density Function

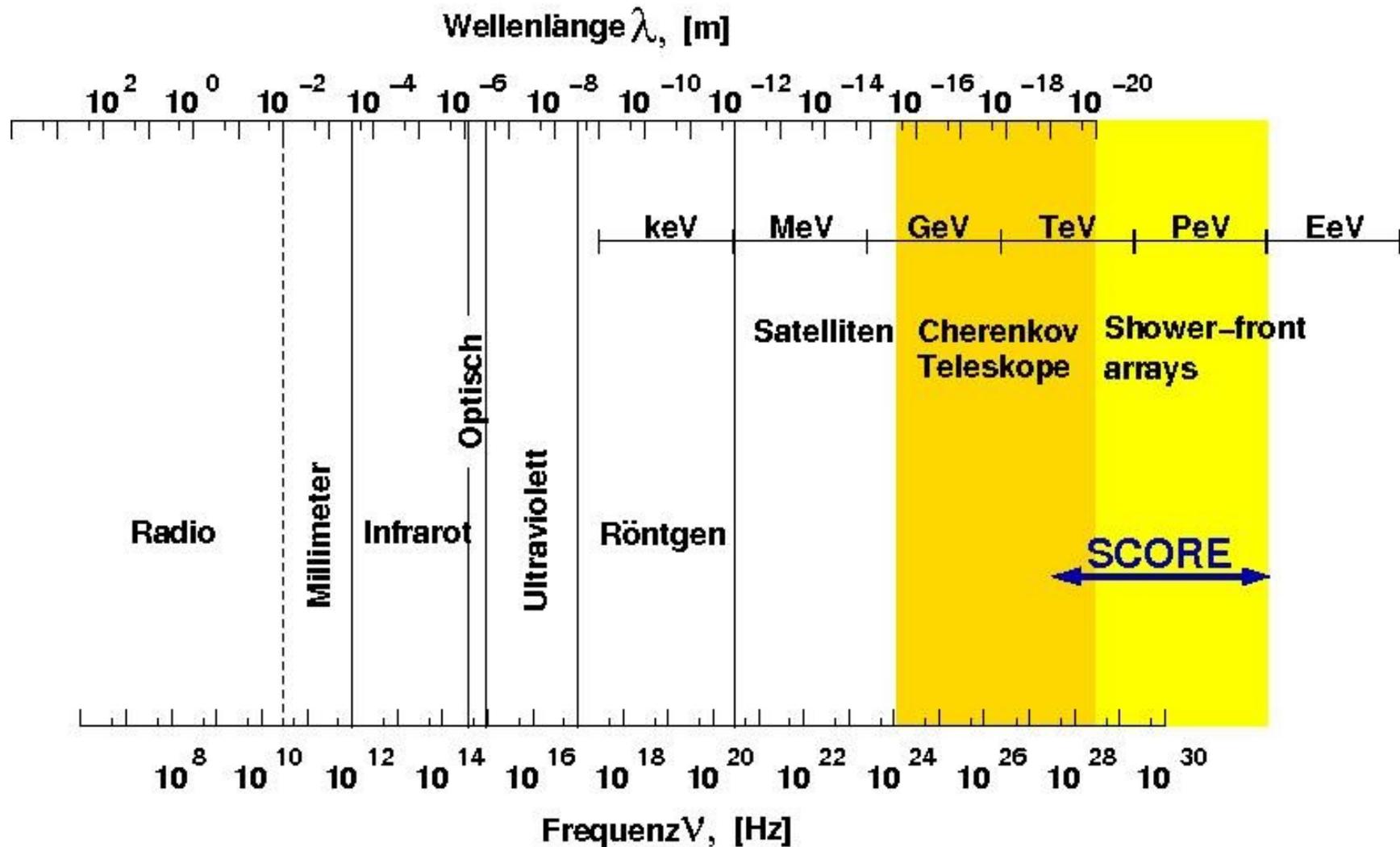


Previous experiments: mainly inner fluctuative part

SCORE: mainly > 120 m (powerlaw, exp)

Advantages: small shower-to-shower fluctuations, large lever arm !

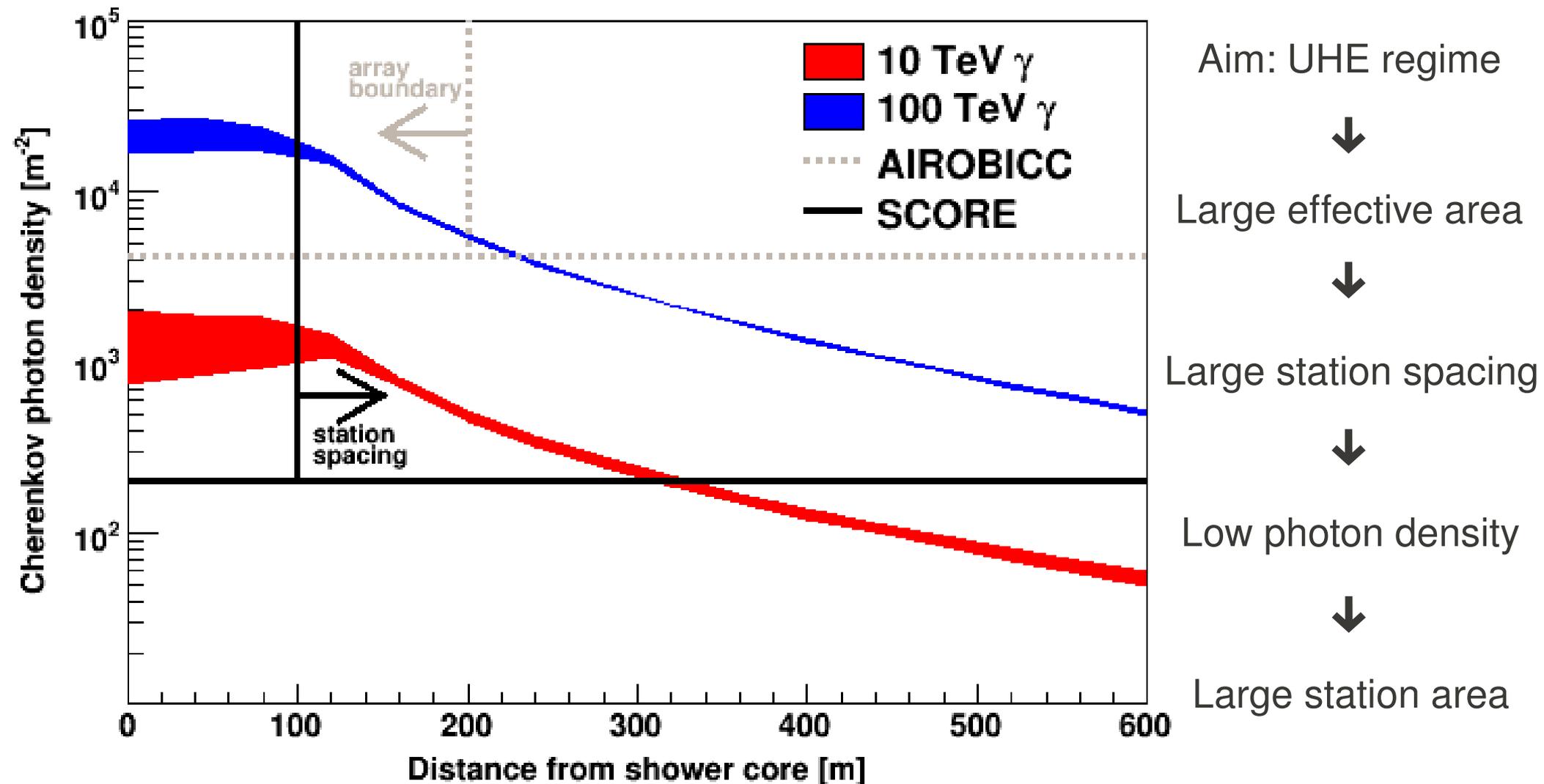
The last Observation Window



SCORE = Study for a Cosmic ORigin Explorer

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

The SCORE Detector



Station Stacking

Many stations with same core distance

Stack stations

Improves S/N

