

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

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Physics motivations

Principle of the array

Status & outlook



Acronyms

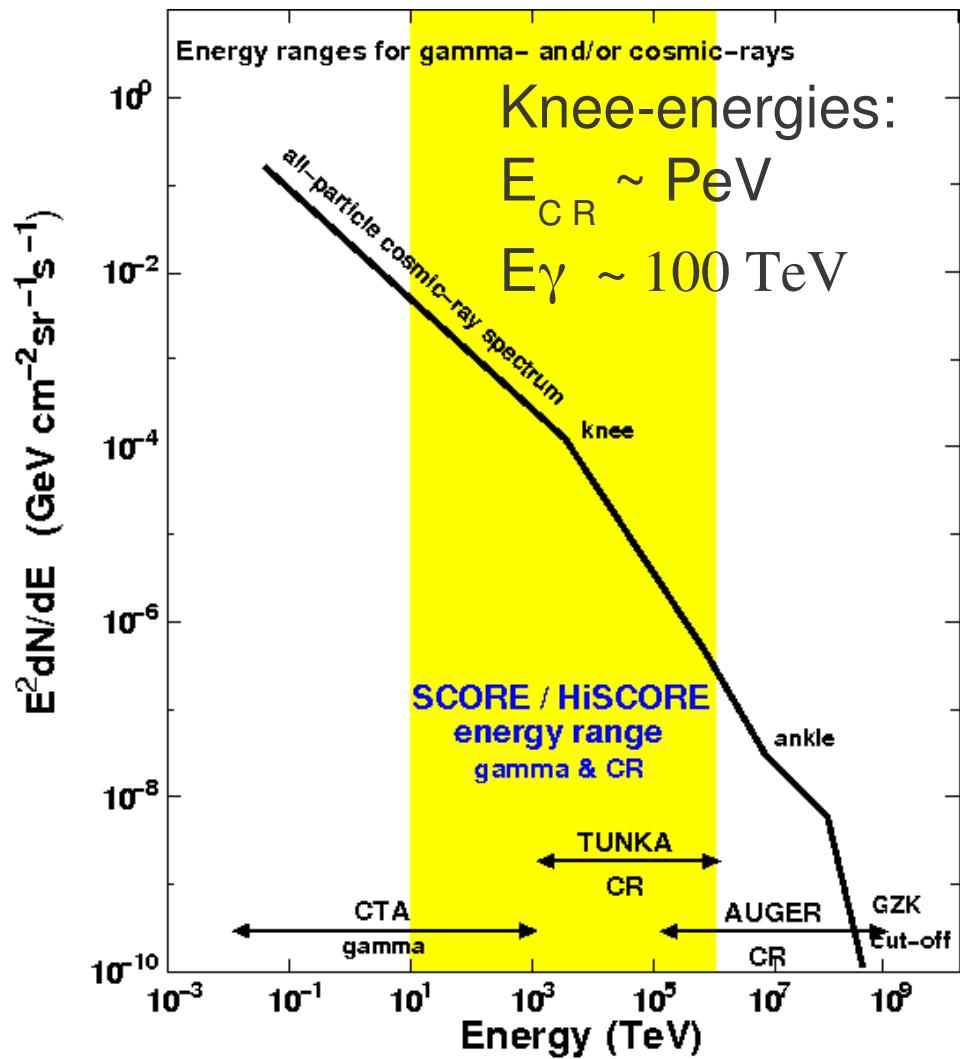
SCORE

Study for a **C**osmic **O**Rigin **E**xplorer $\sim 10 \text{ km}^2$

HiSCORE

Hundred***i** **S**quare-km **C**osmic **O**Rigin **E**xplorer $\sim 100+ \text{ km}^2$

HiSCORE aims



Cosmic-rays:

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

Gamma-rays:

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

Large area: $10\text{-}100 \text{ km}^2$

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



Astroparticle Physics @ $E > 10 \text{ TeV}$

Gamma-ray Astronomy

VHE spectra: where do they stop ?

Origin of cosmic rays: pevatrons

Absorption in IRF & CMB

Diffuse emission:

Galactic plane

Local supercluster

Particle physics beyond LHC

Axion / photon conversion

Hidden photon / photon oscillations

Lorentz invariance violation

pp cross-section measurements

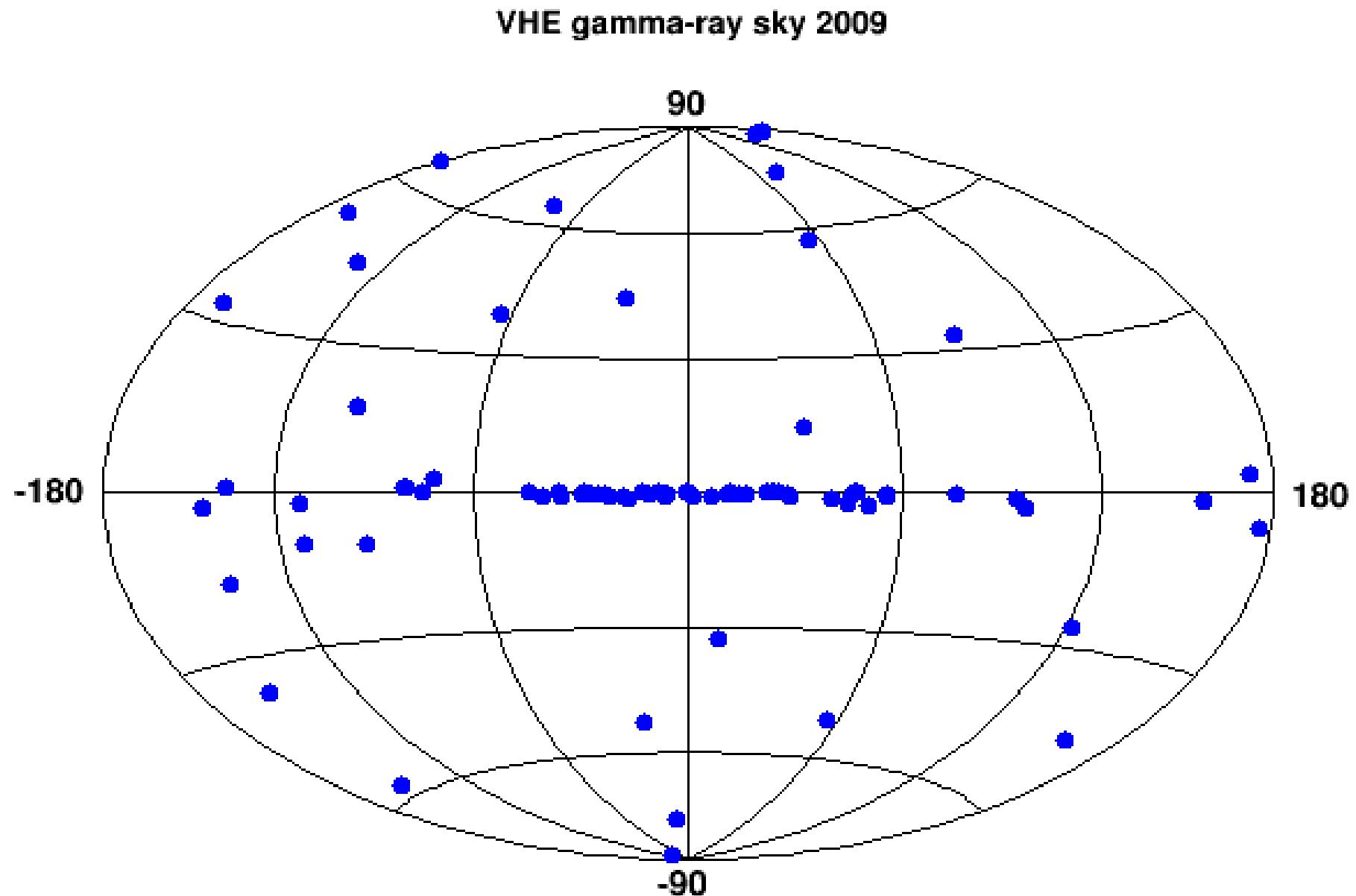
Quark-gluon plasma

Charged cosmic ray physics

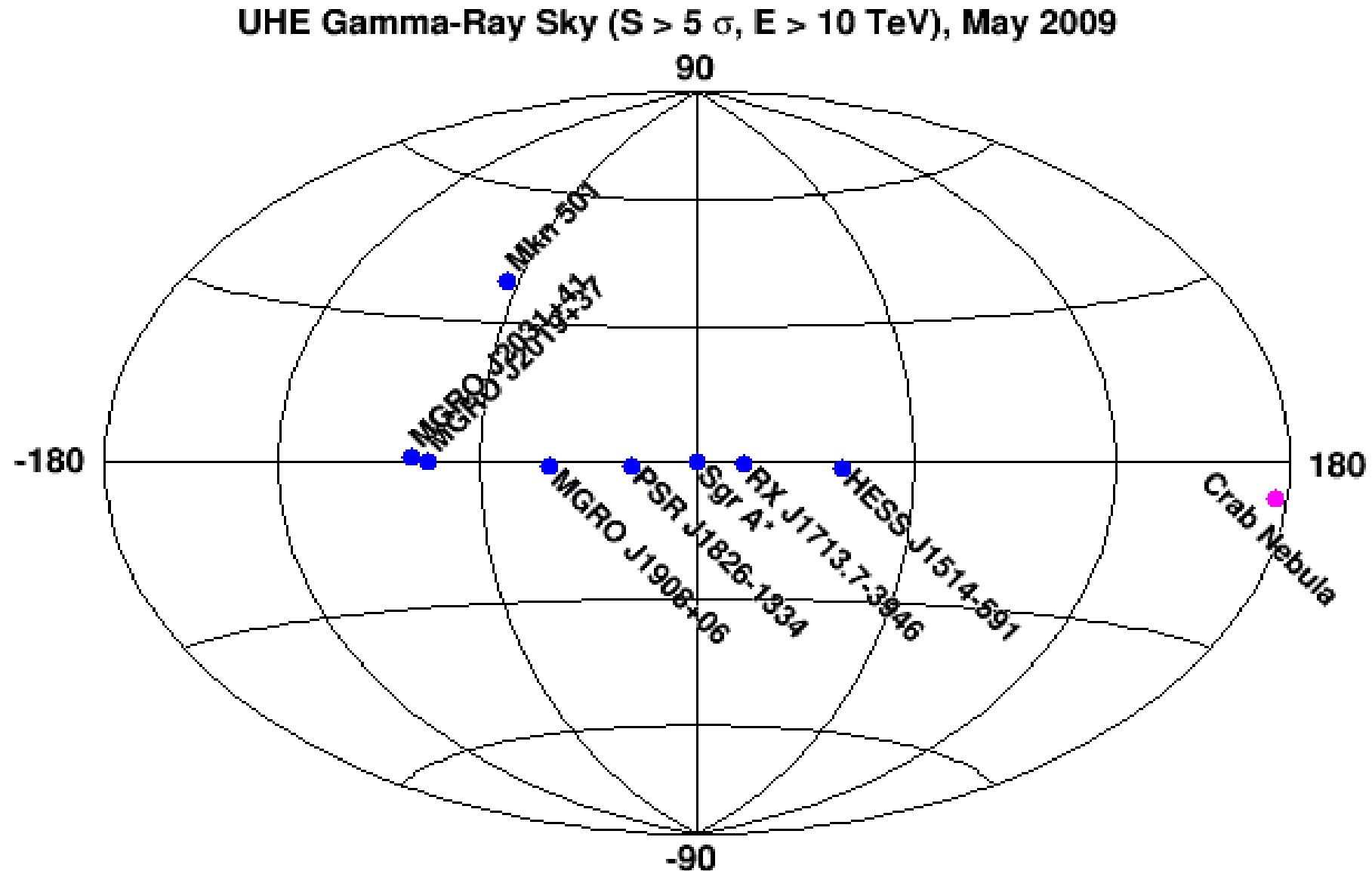
Composition / anisotropies

Sub-knee to pre-ankle

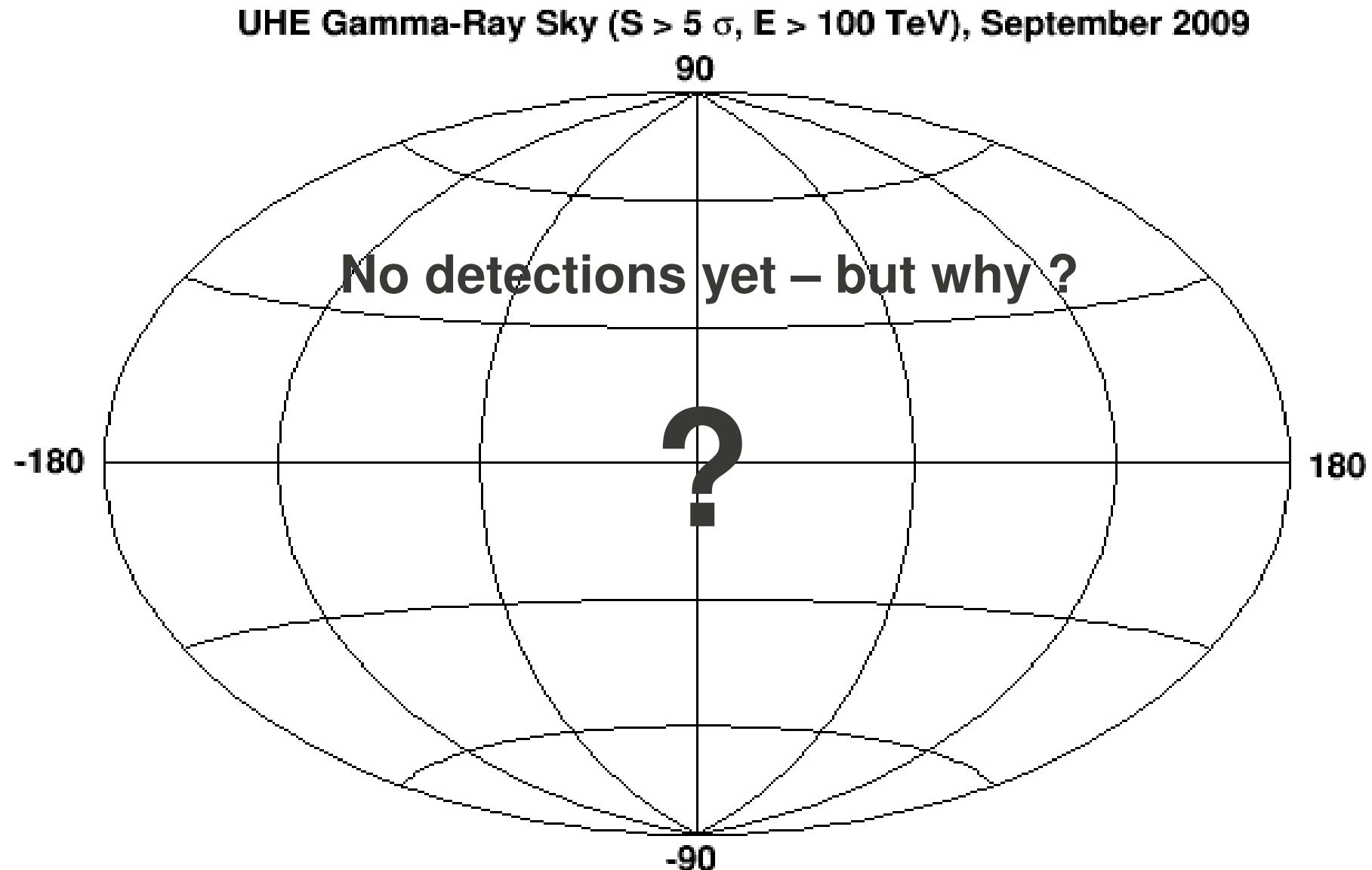
Gamma-Ray Sky, E>100GeV



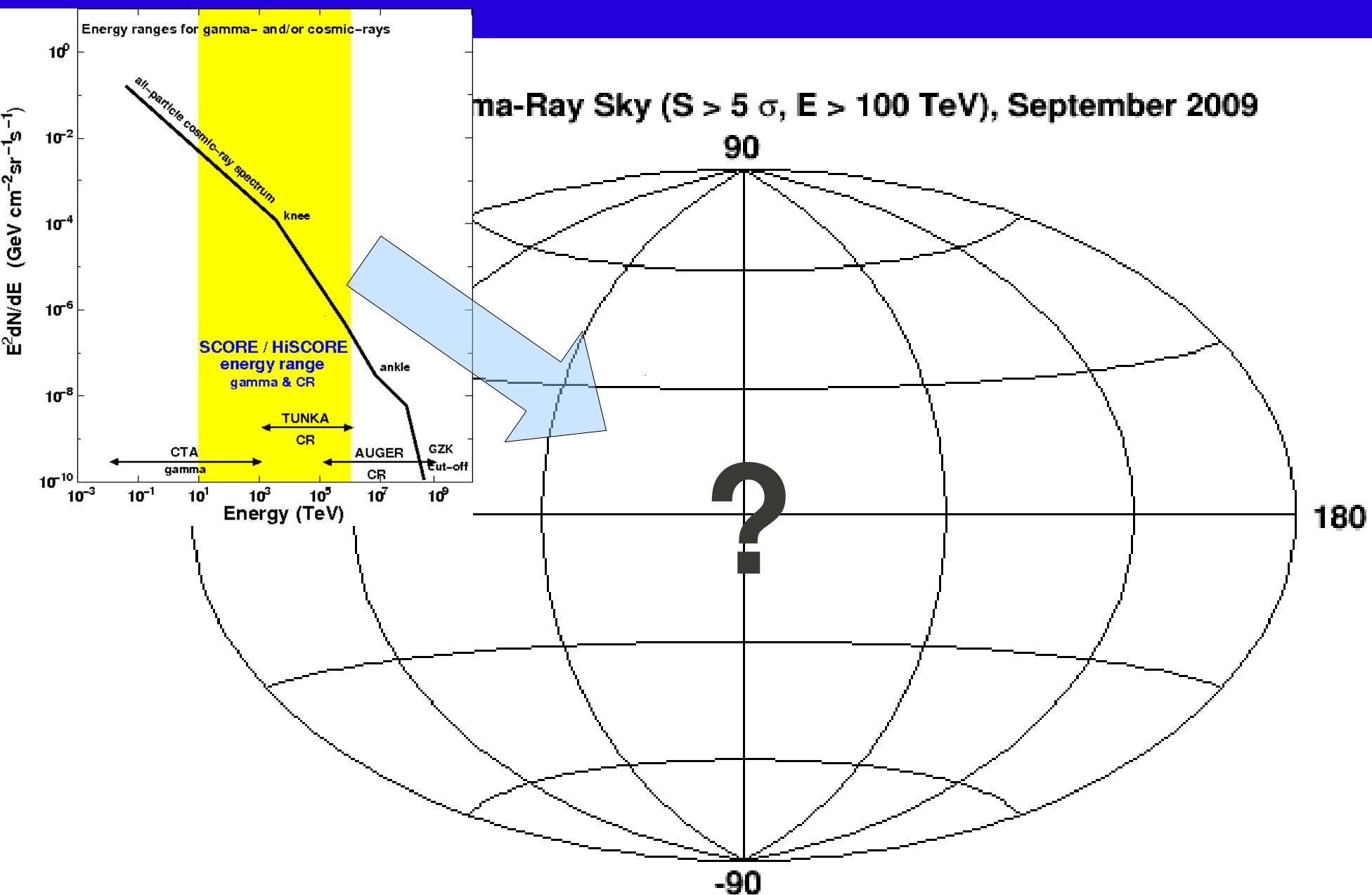
Gamma-Ray Sky, E>10TeV



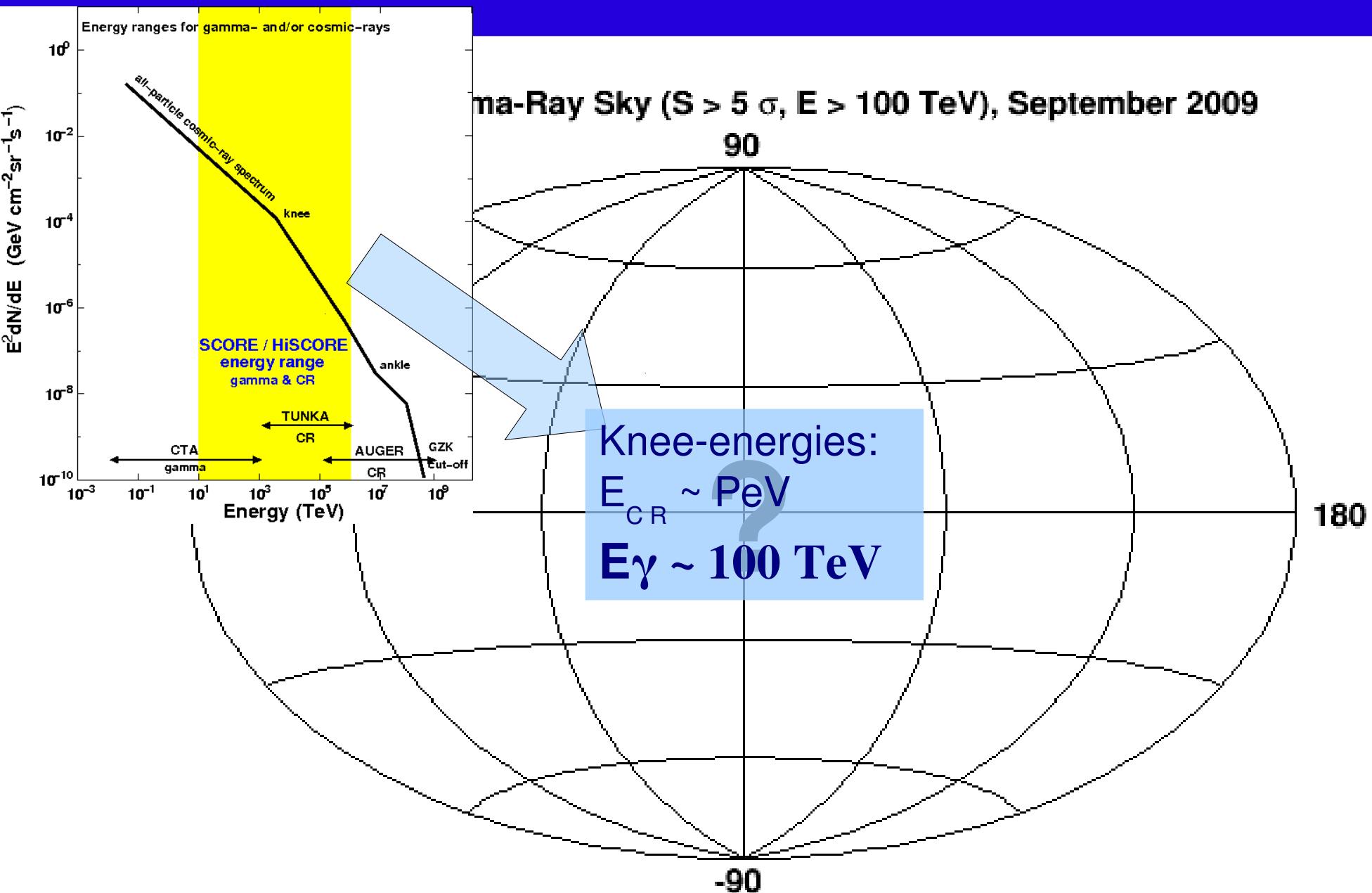
Gamma-Ray Sky, $E > 100 \text{ TeV}$



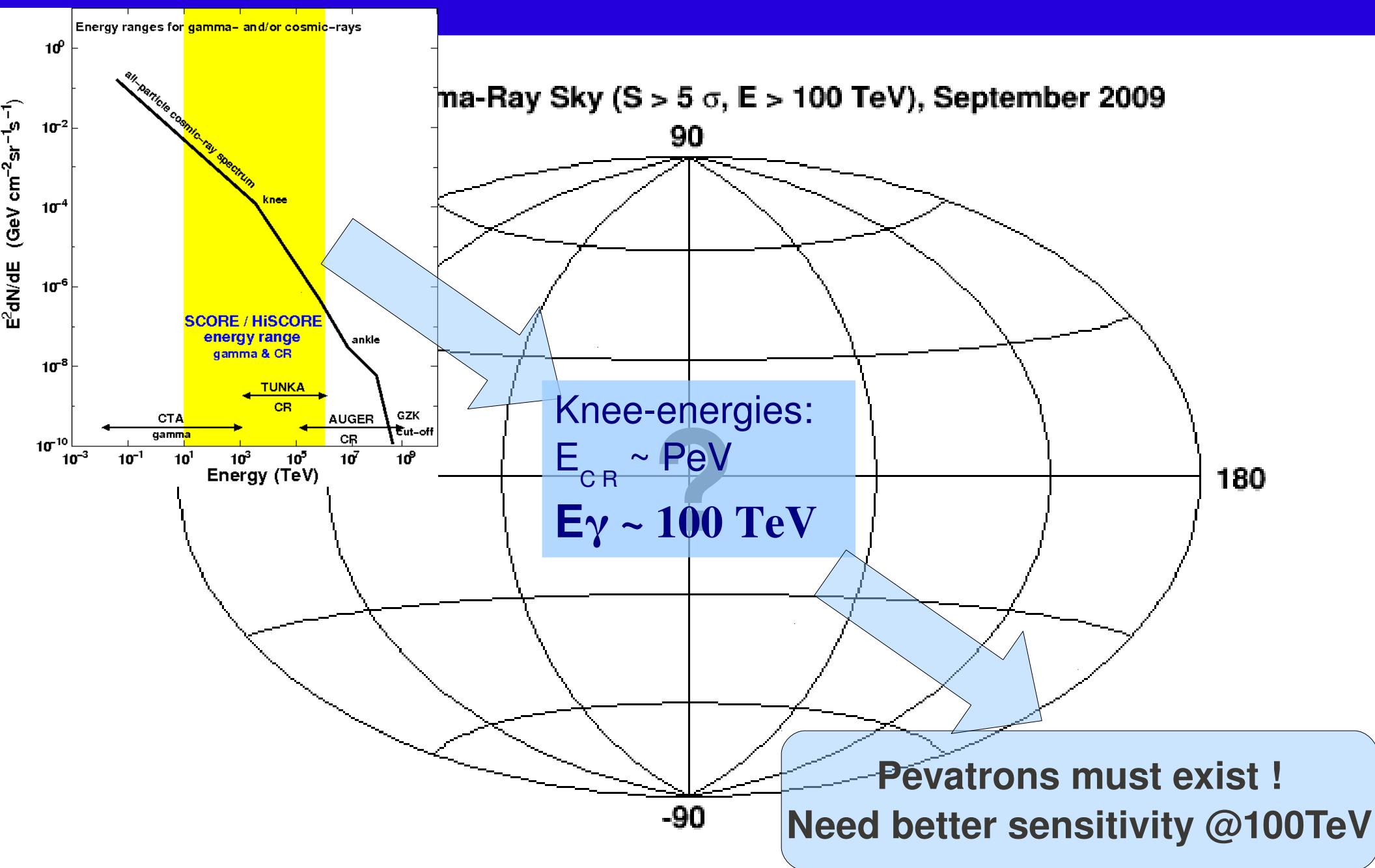
Gamma-Ray Sky, E>100TeV



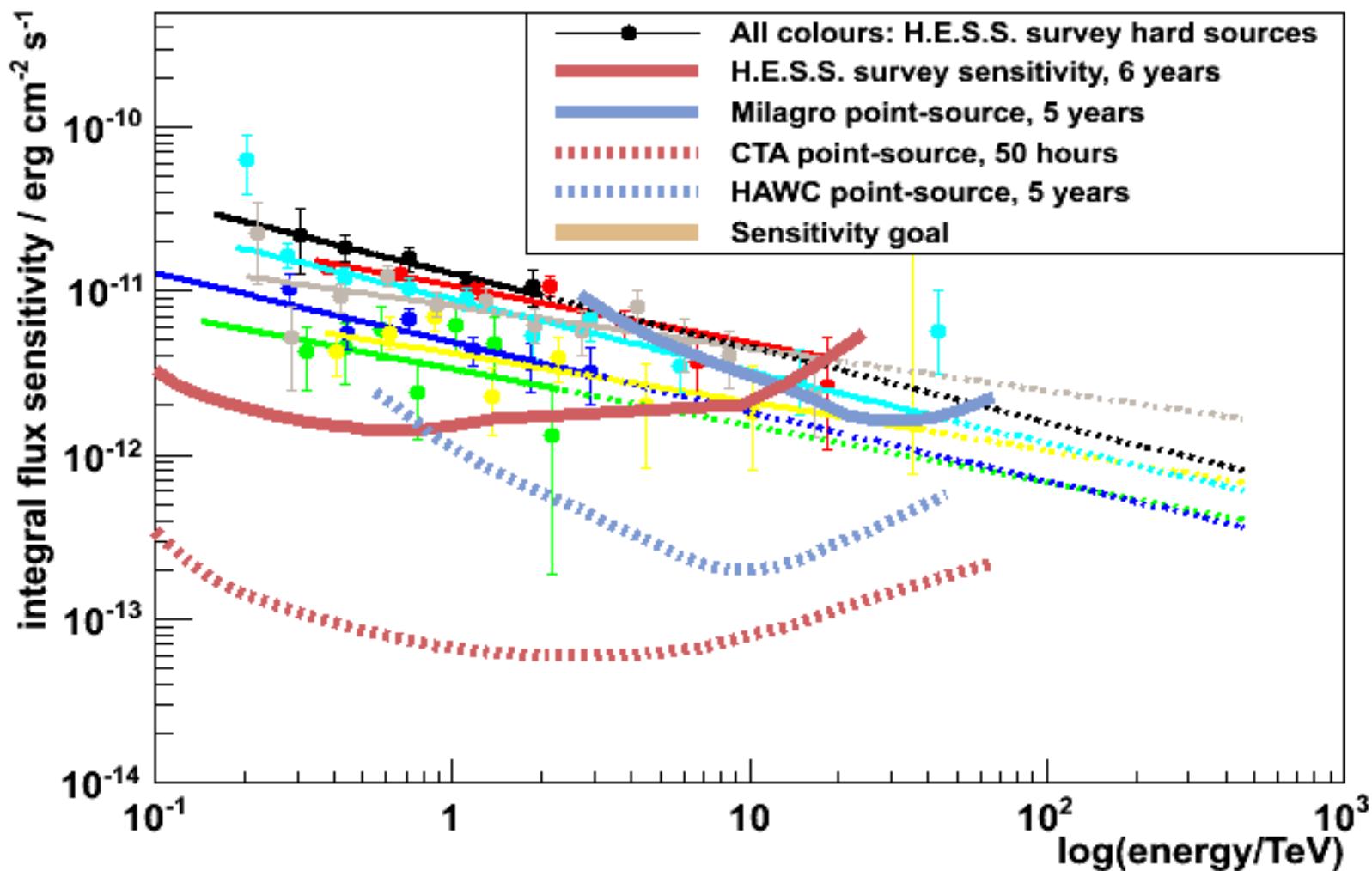
Gamma-Ray Sky, $E > 100 \text{ TeV}$



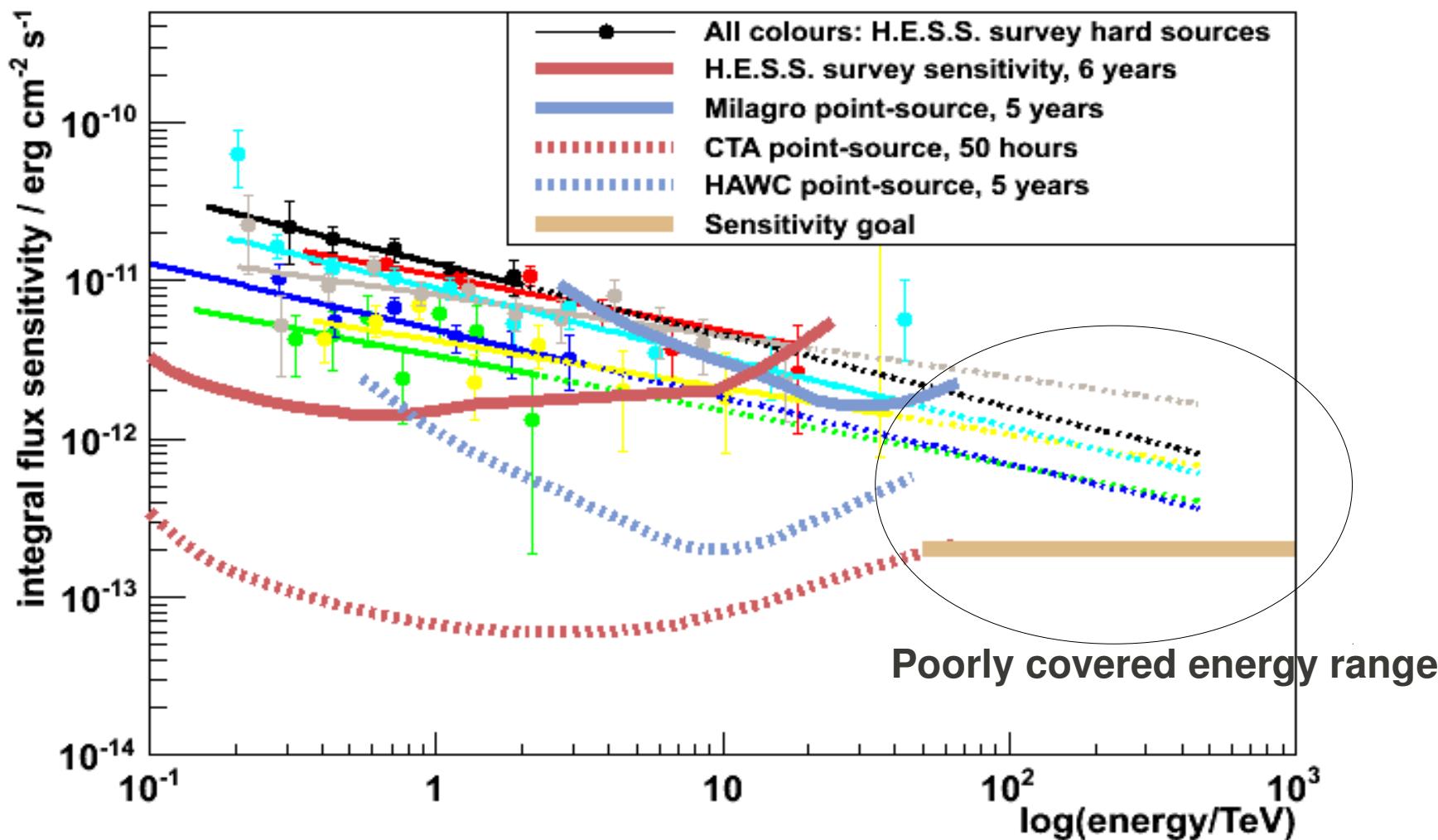
Gamma-Ray Sky, $E > 100 \text{ TeV}$



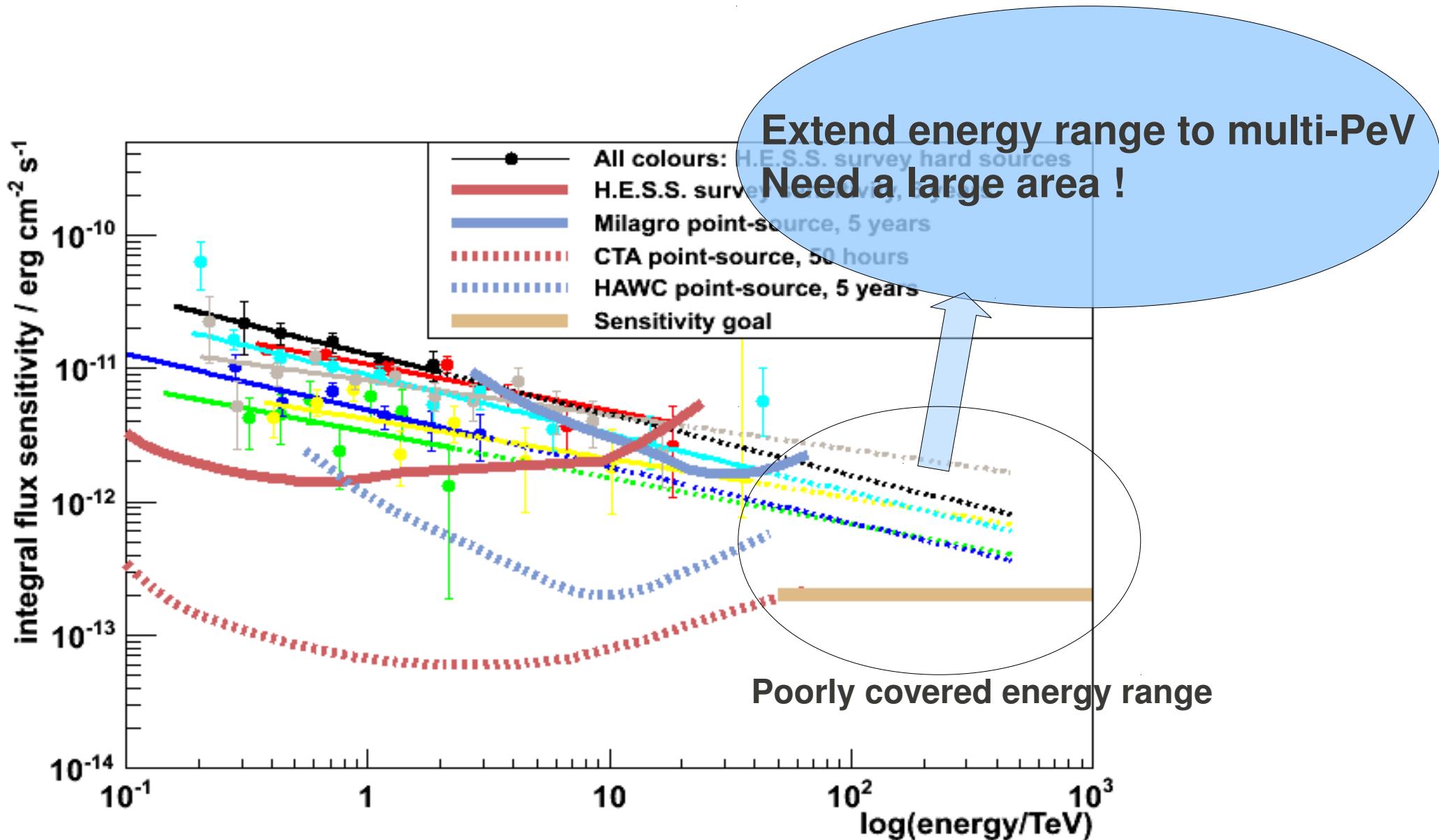
UHE Gamma-rays



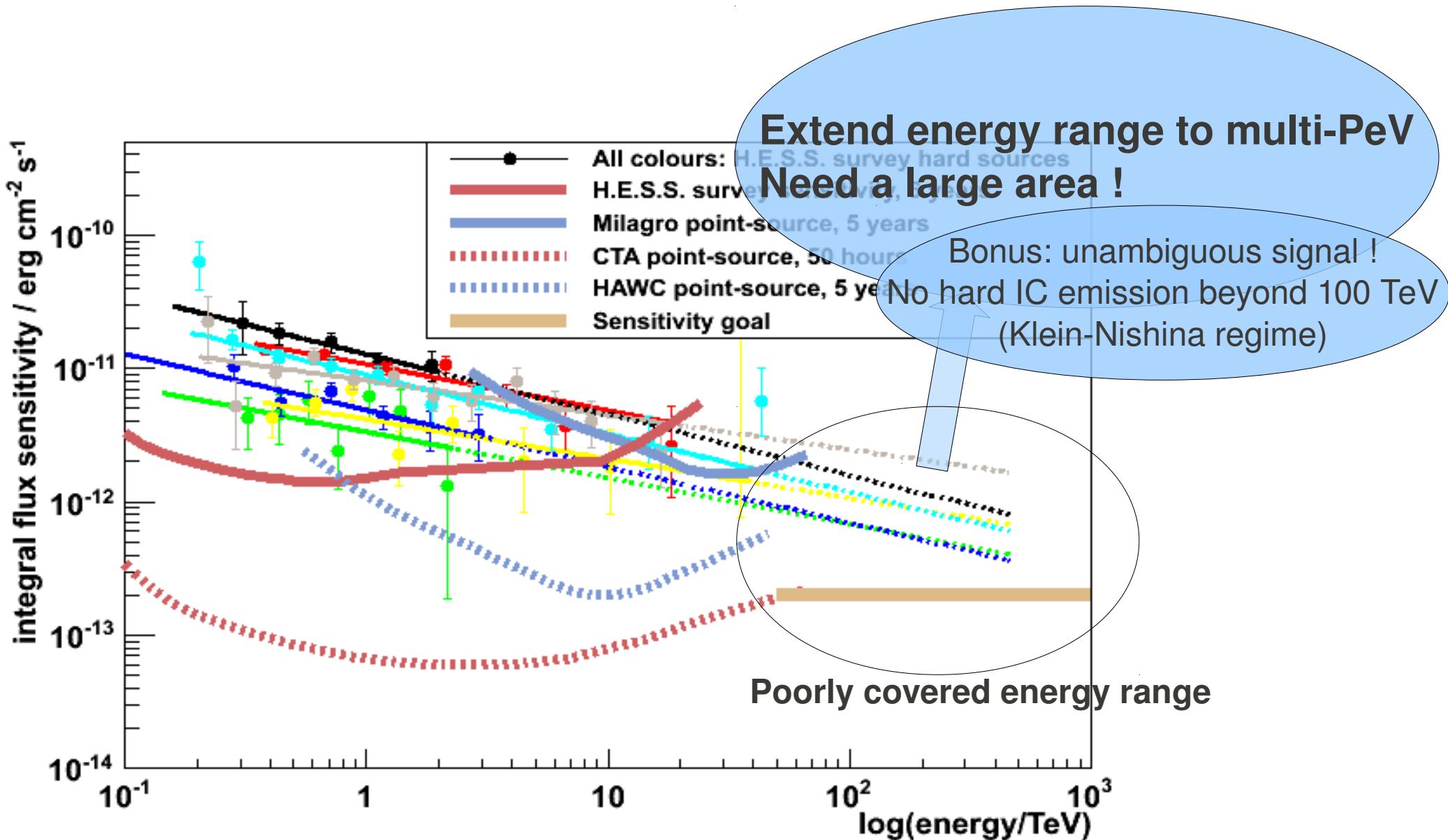
UHE Gamma-rays



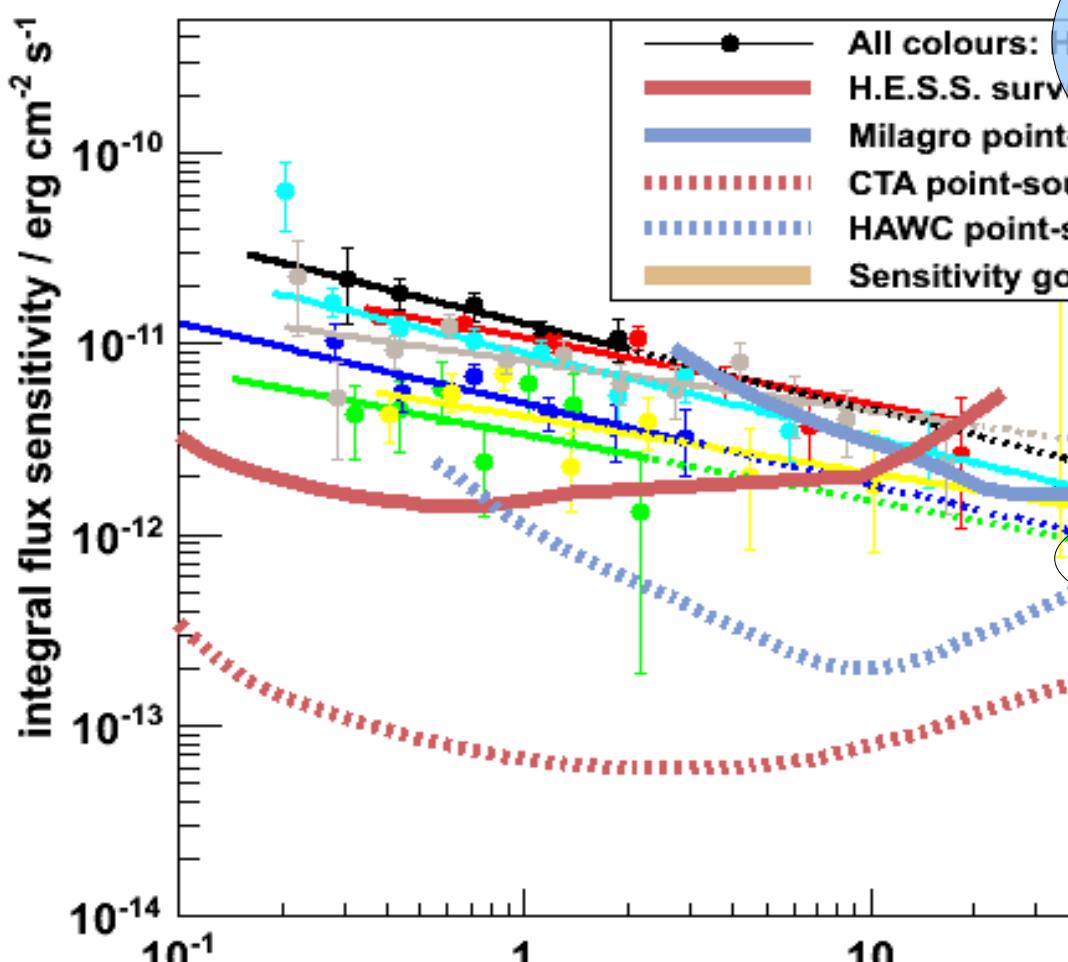
UHE Gamma-rays



UHE Gamma-rays

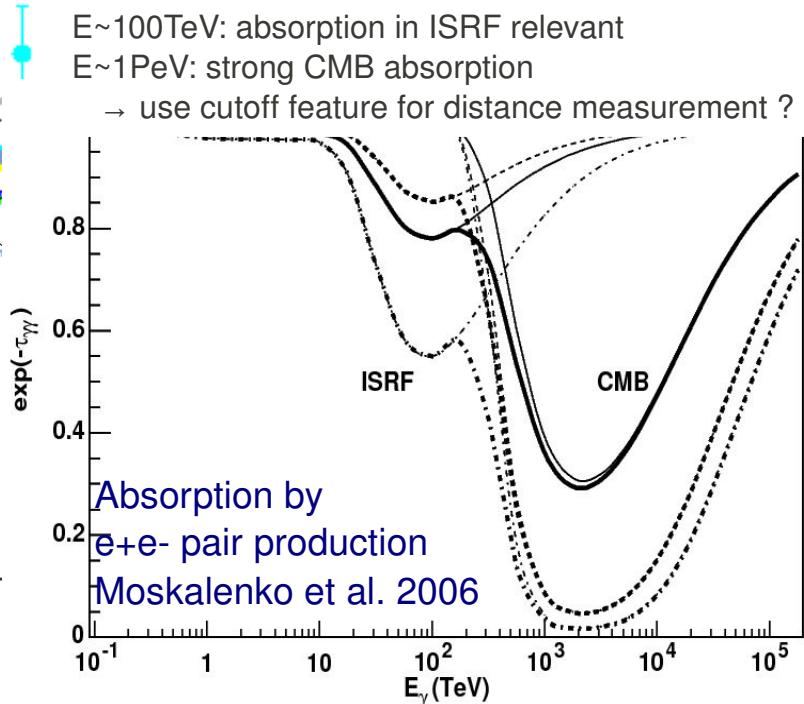


UHE Gamma-rays

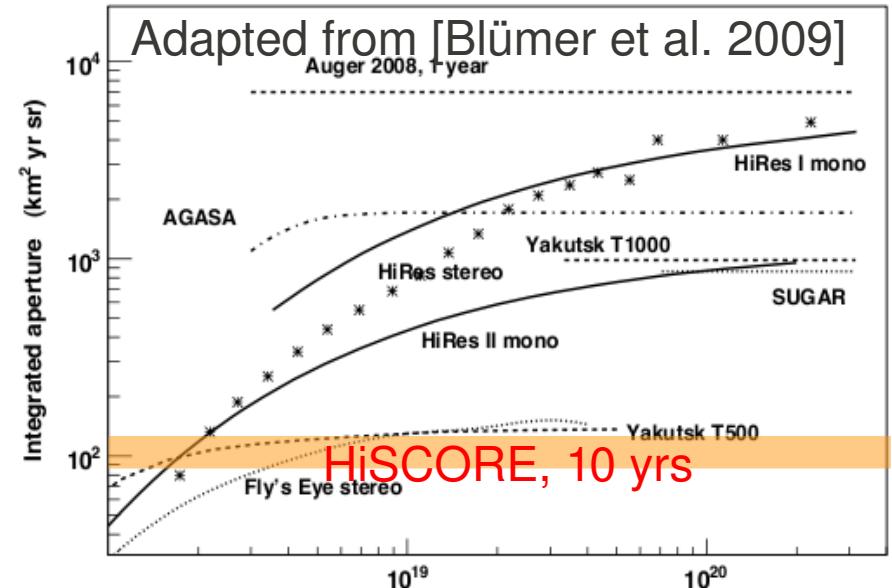
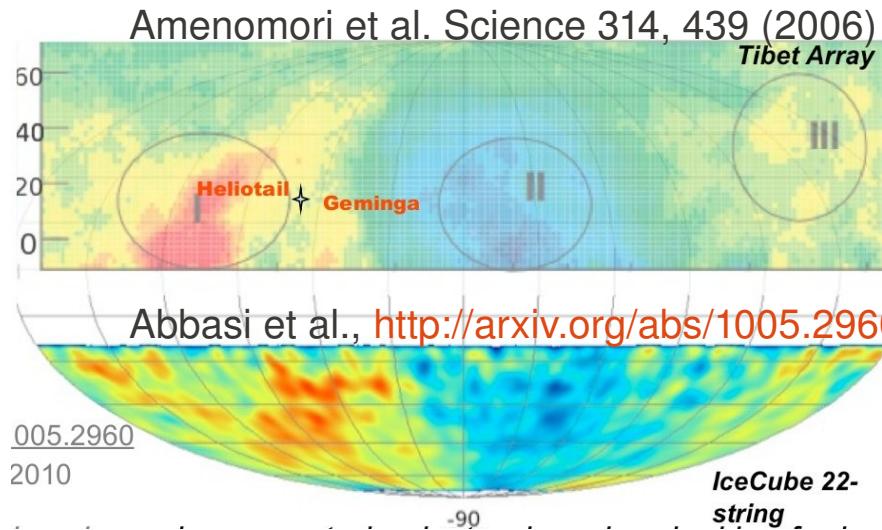
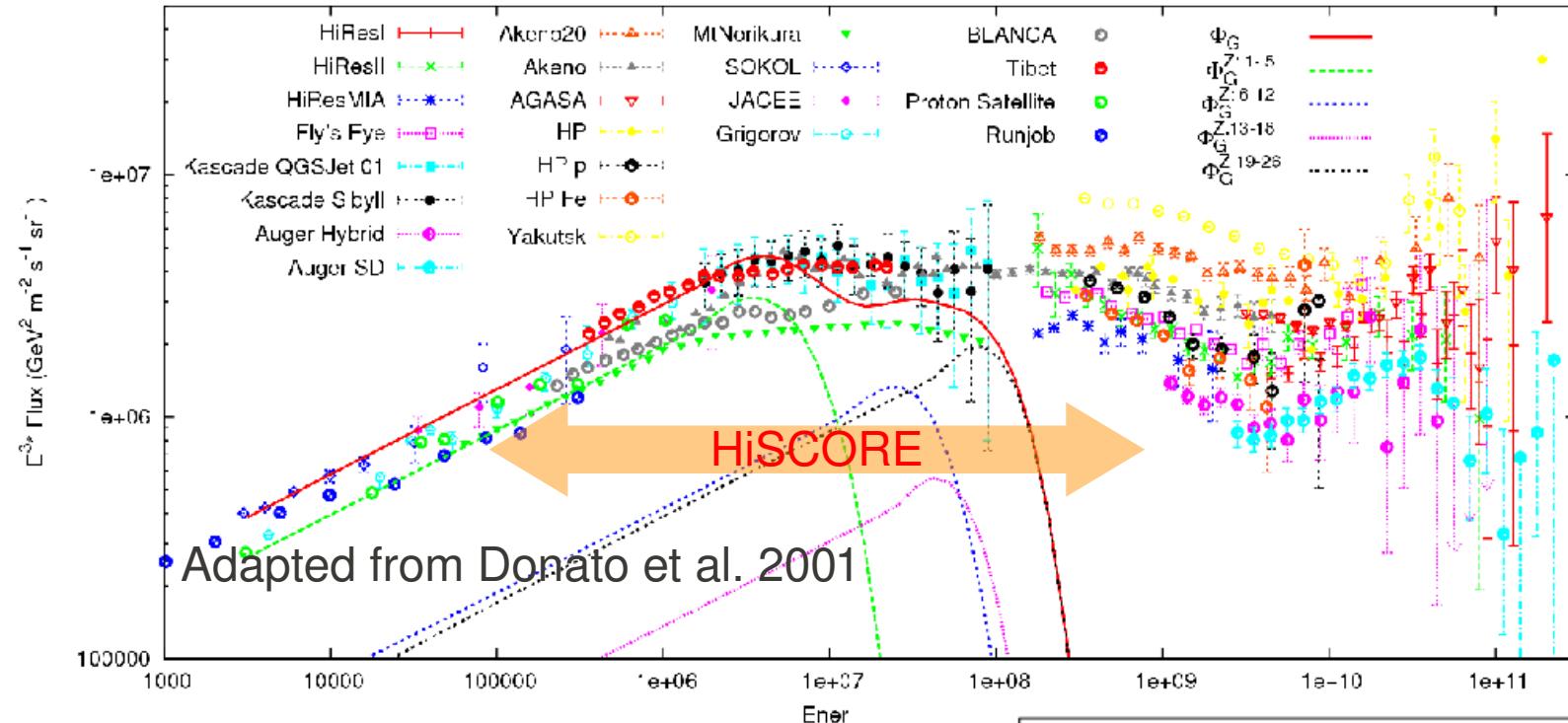


Extend energy range to multi-PeV
Need a large area !

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

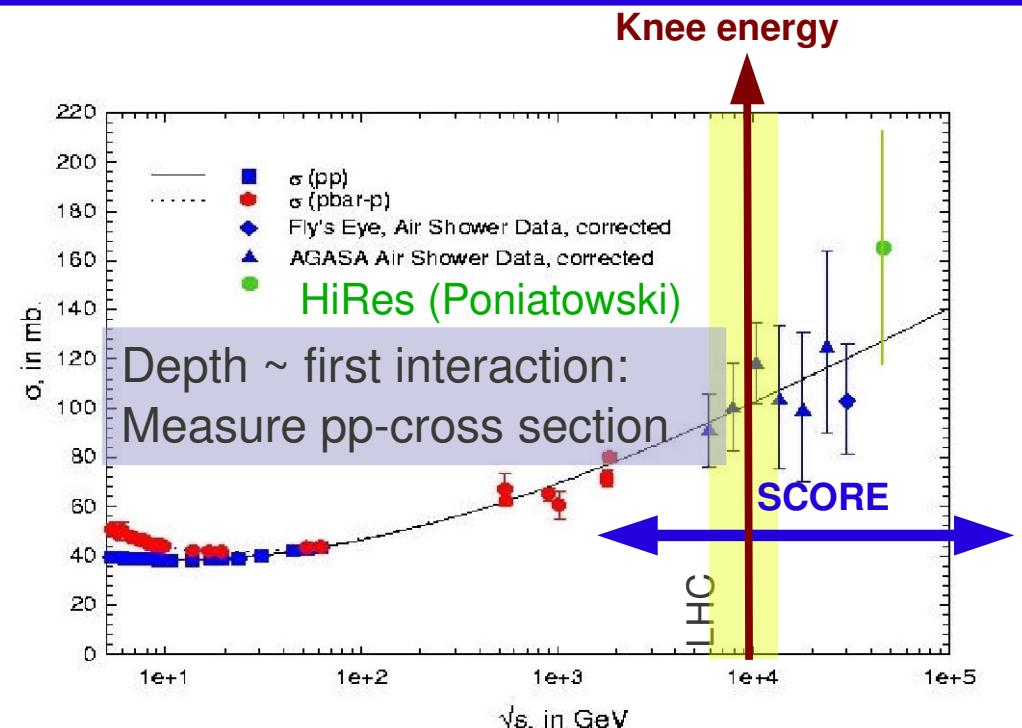
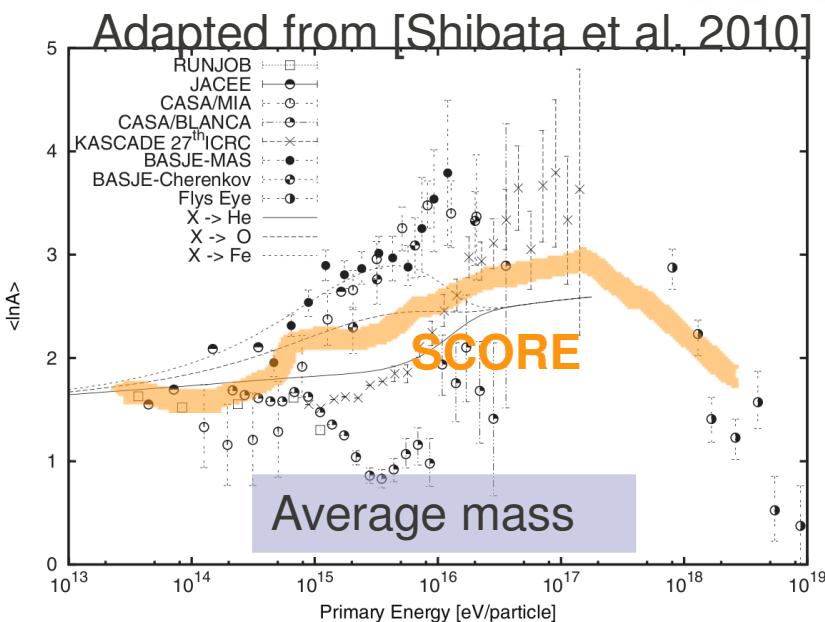
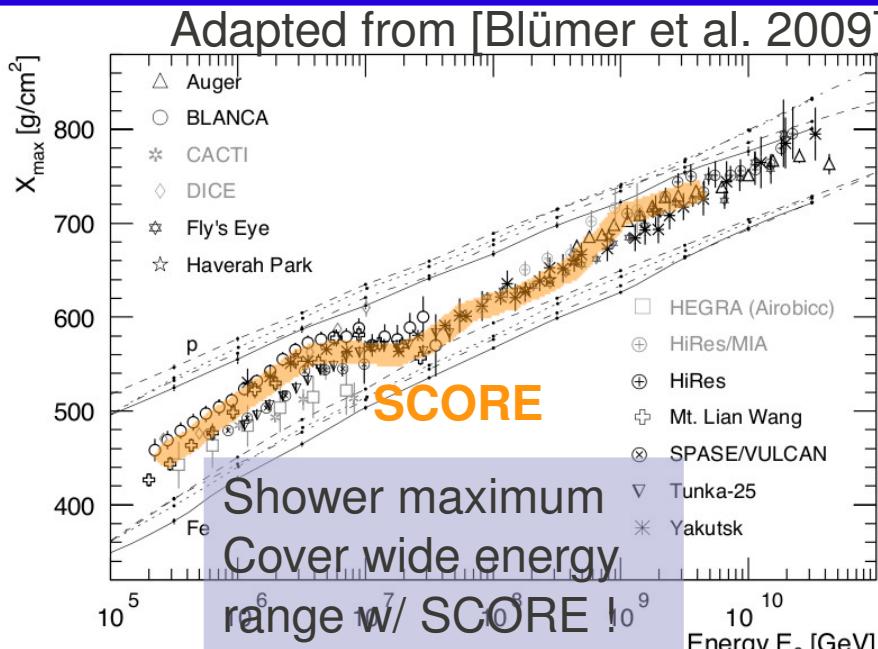


Cosmic rays



Cosmic rays

Particle physics



The detector

Goals:

Energy range goal: 10 TeV – 1 EeV

Area goal: 10 – 100+ km²

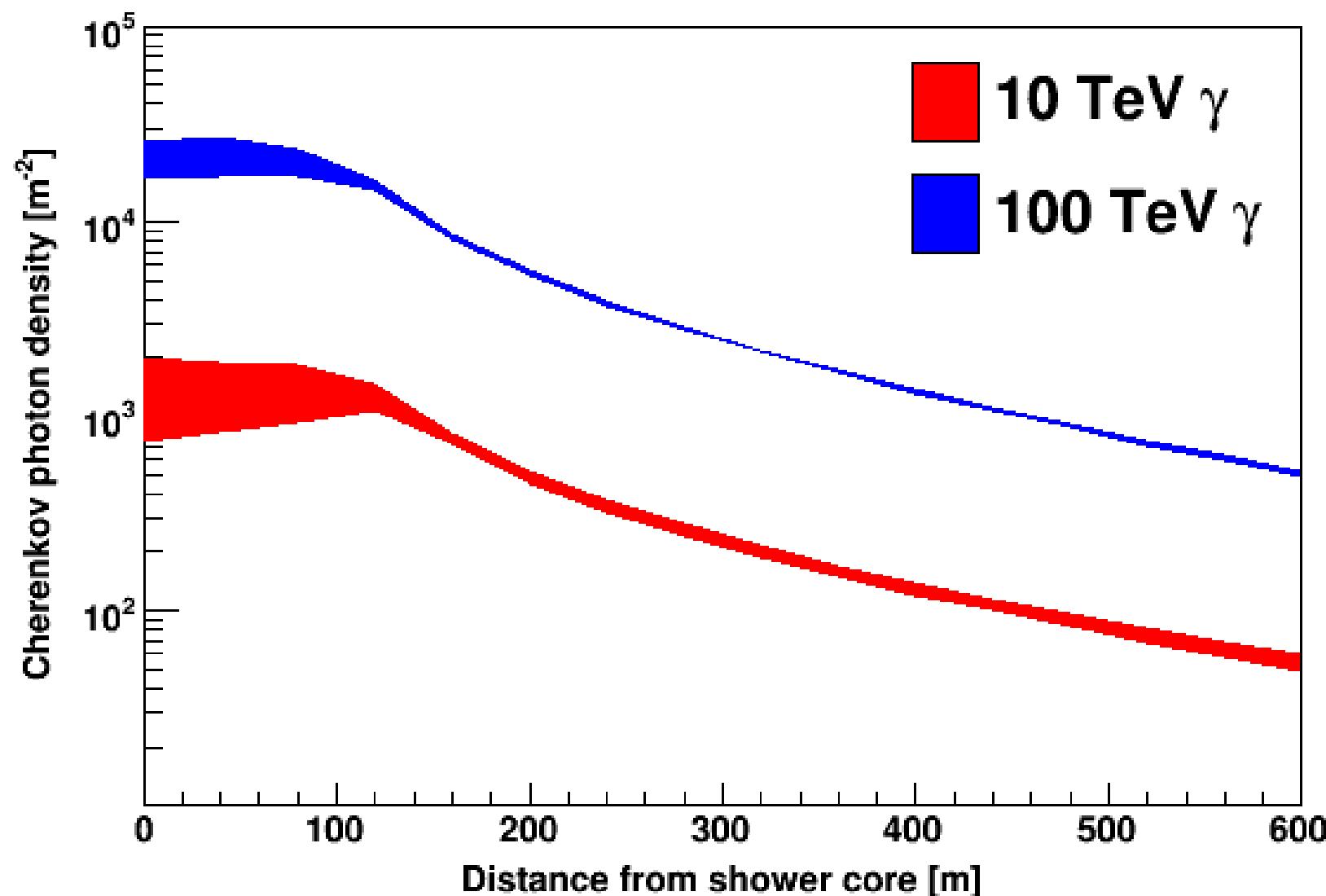
Sensitivity goal: better than 10^{-12} erg / cm² s

Concept:

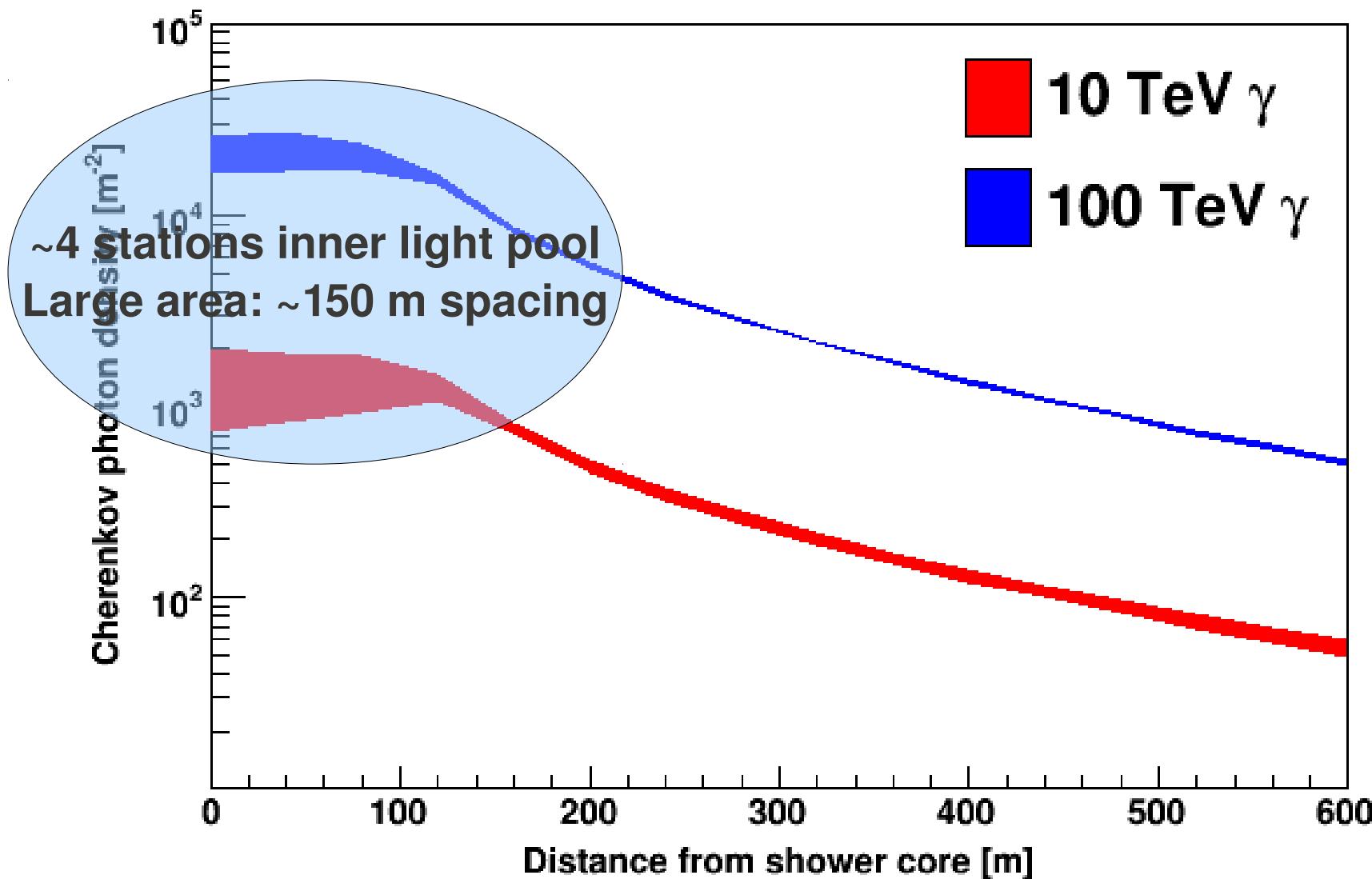
Very large effective area, wide field of view

Non-imaging atmospheric Cherenkov technique

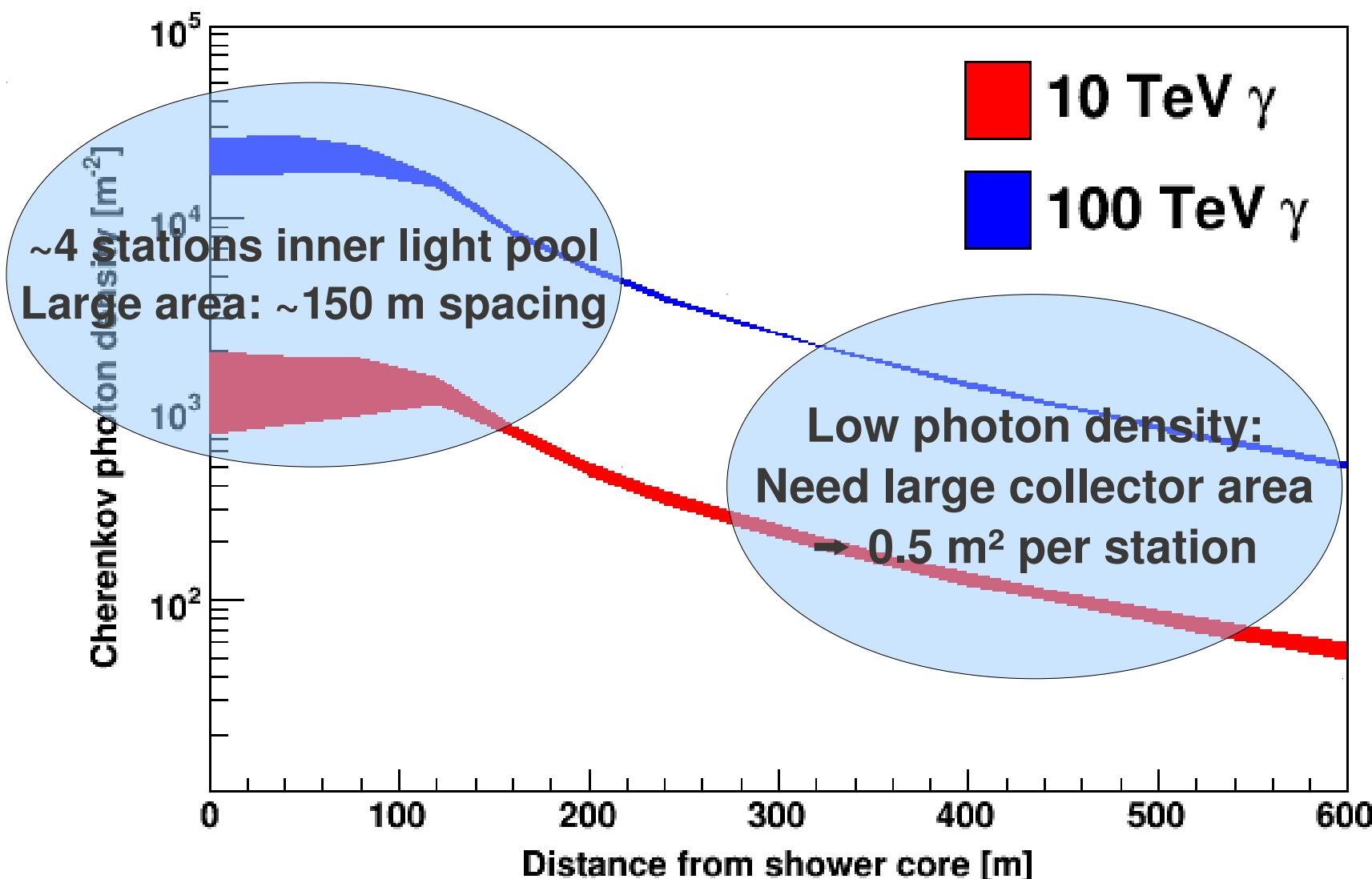
Lateral Cherenkov Photon Distribution



Lateral Cherenkov Photon Distribution



Lateral Cherenkov Photon Distribution



The HiSCORE principle

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

Imaging ACTs: > 10000 channels / km²

Non-imaging Cherenkov light-front sampling

SCORE: ~300 channels / km²

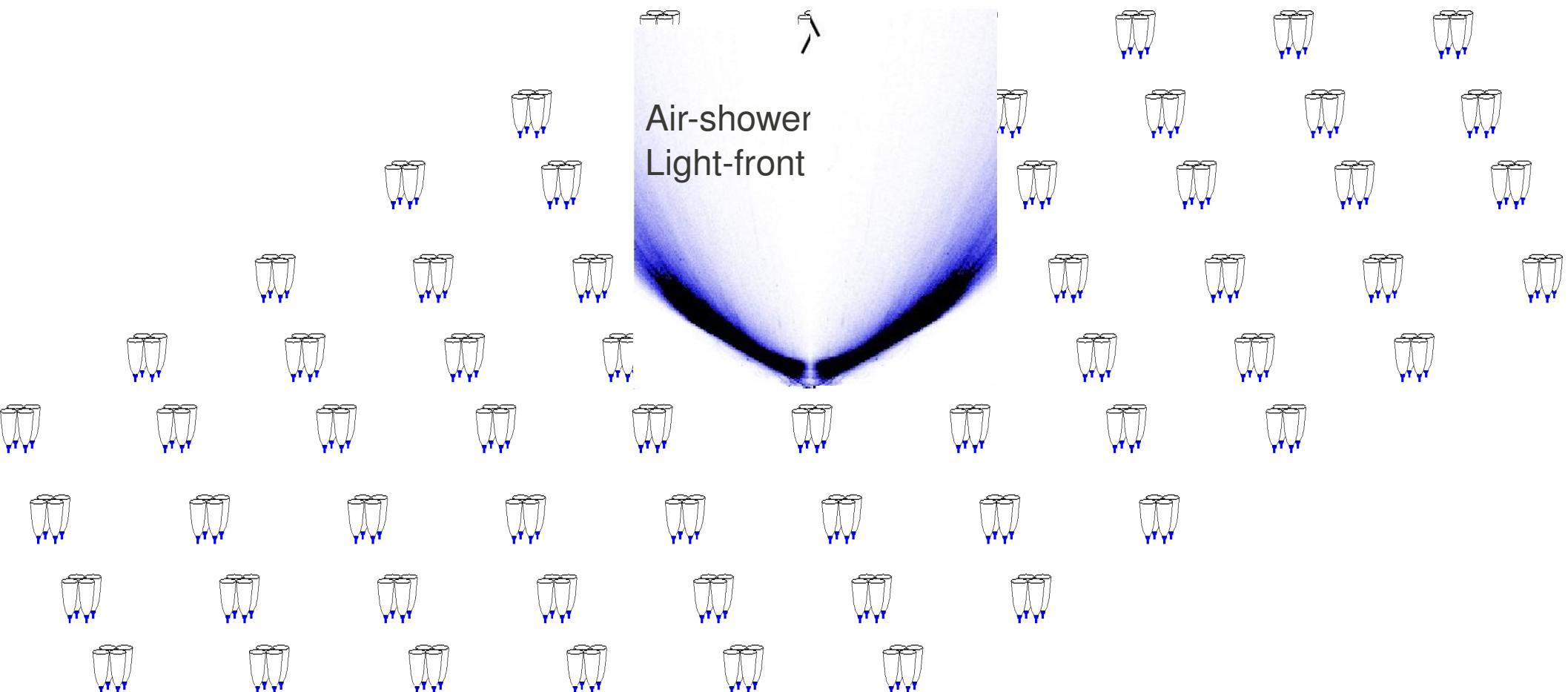


The HiSCORE principle

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

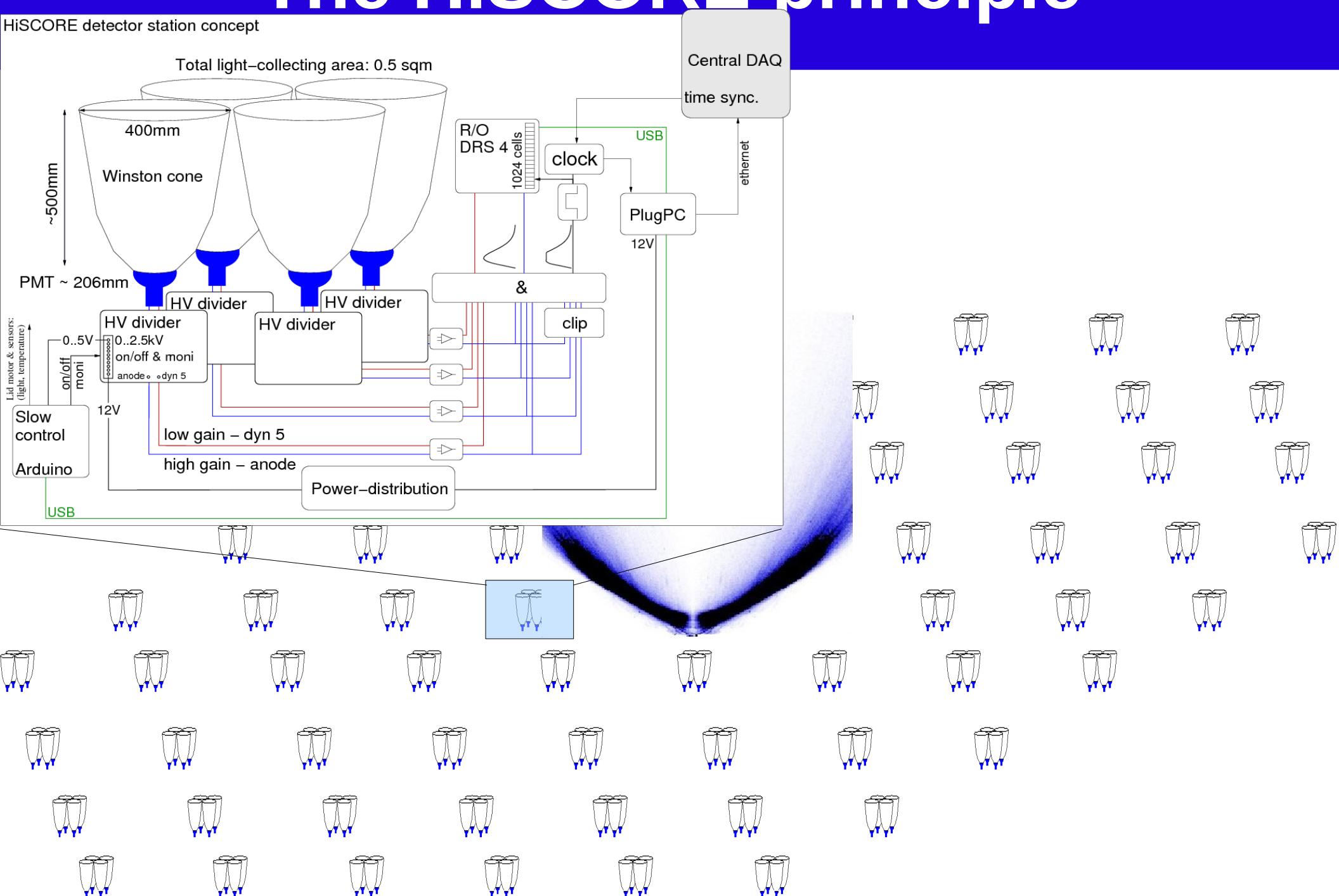
Imaging ACTs: > 10000 channels / km²

Non-imaging Cherenkov light-front sampling – record light amplitude and timing
SCORE: ~300 channels / km²



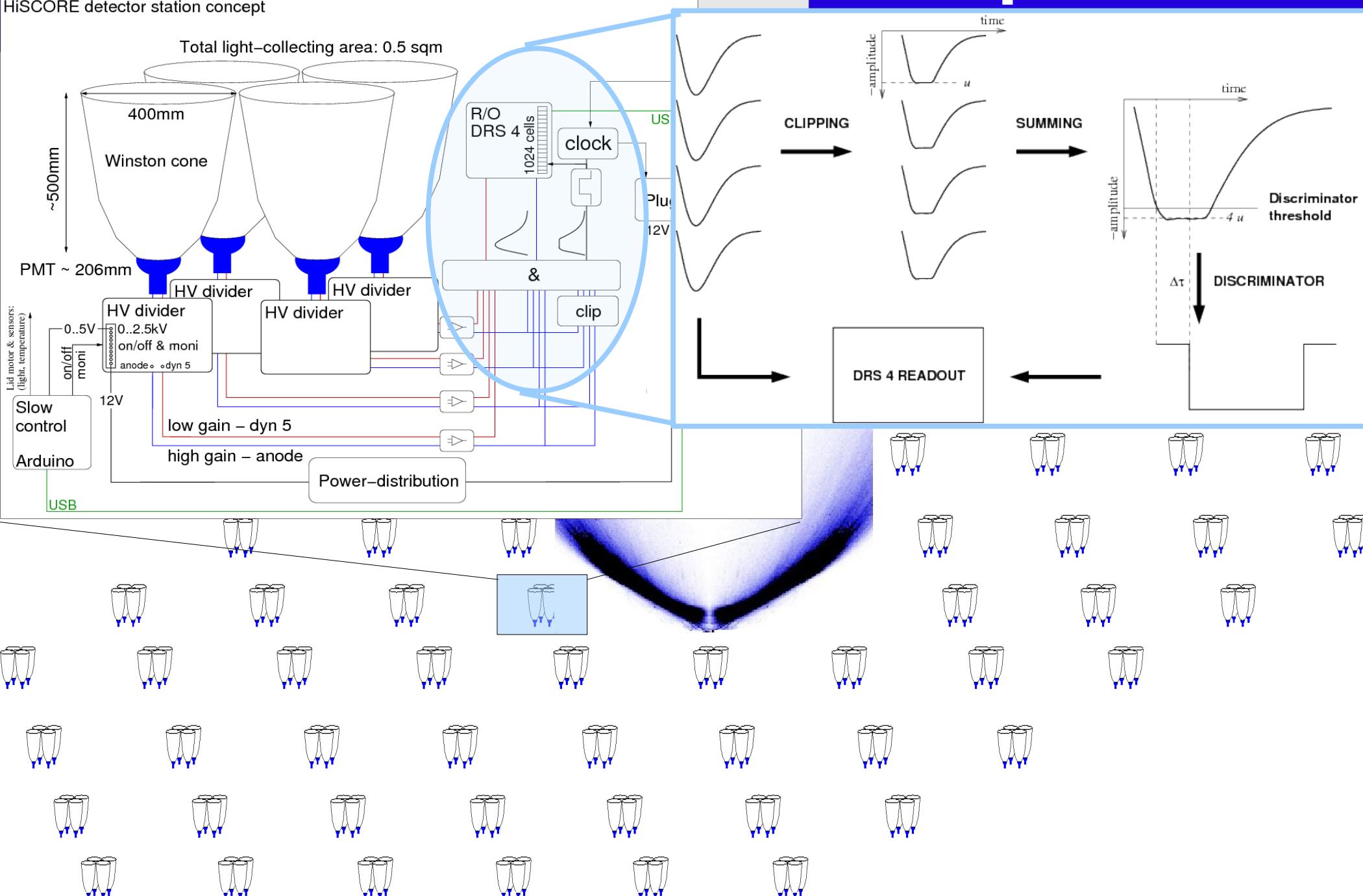
The HiSCORE principle

HiSCORE detector station concept

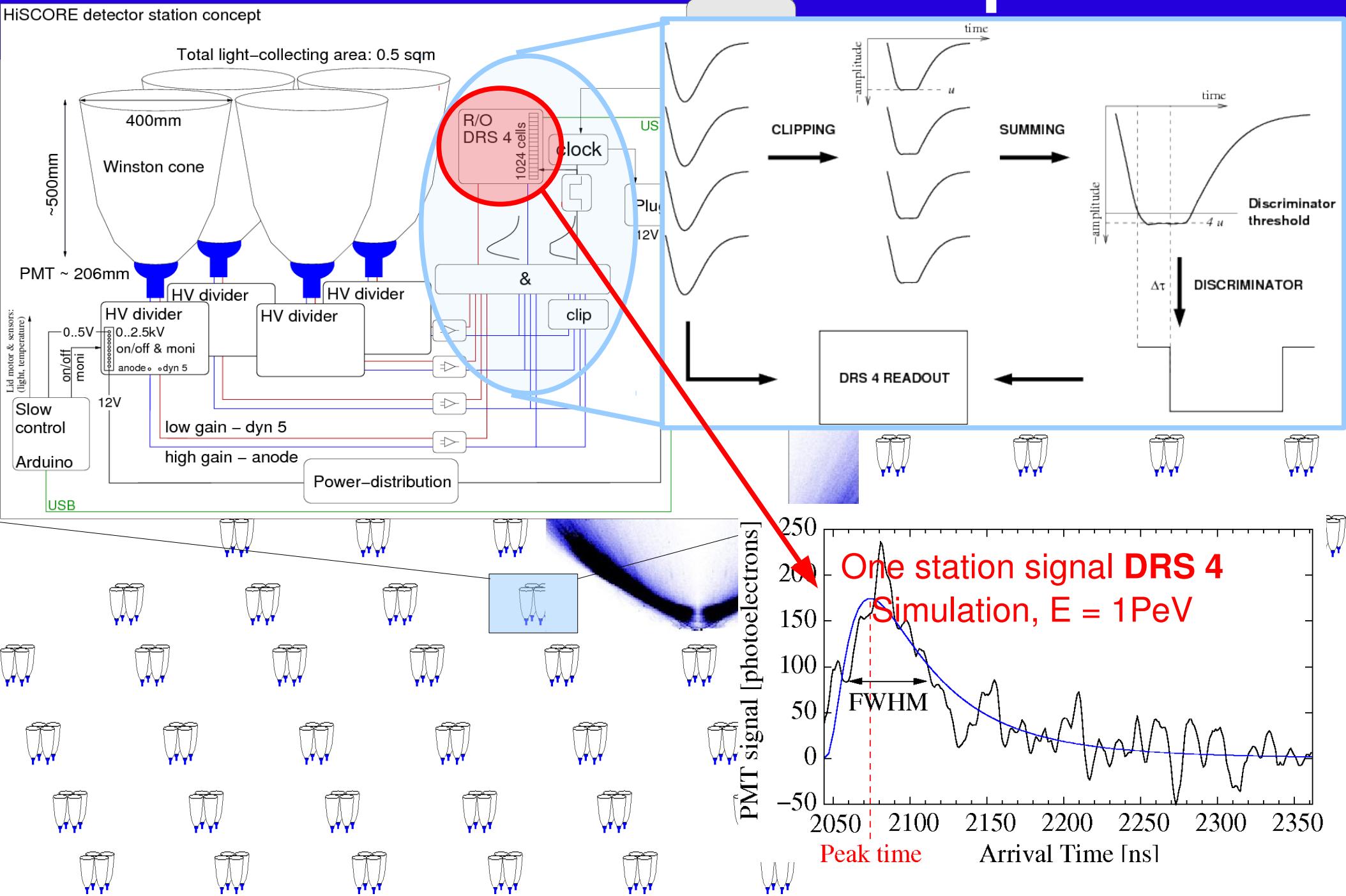


The HiSCORE principle

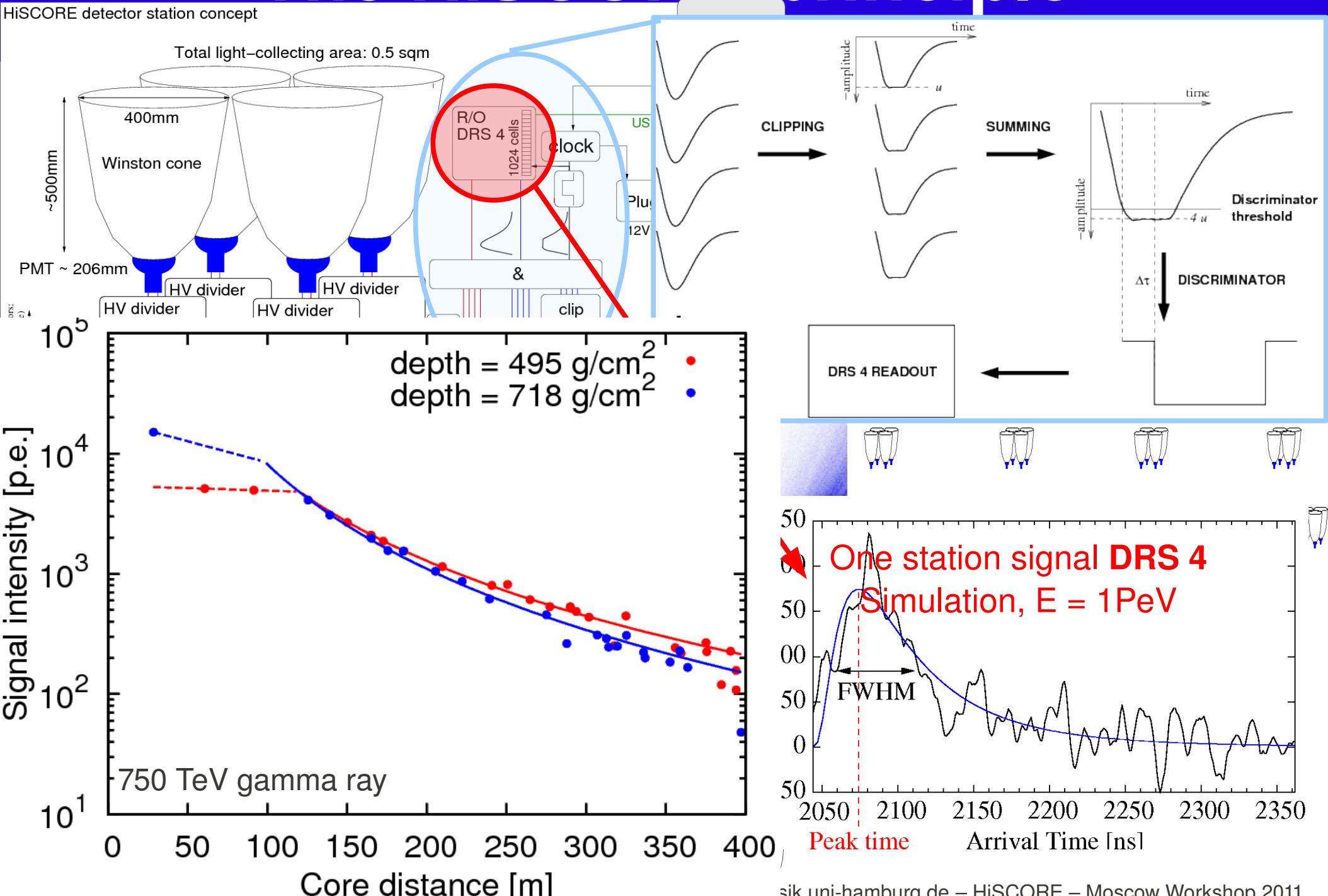
HiSCORE detector station concept



The HiSCORE principle



The HiSCORE principle



Shower simulation

Air-shower simulation CORSIKA 6735 [1]:

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

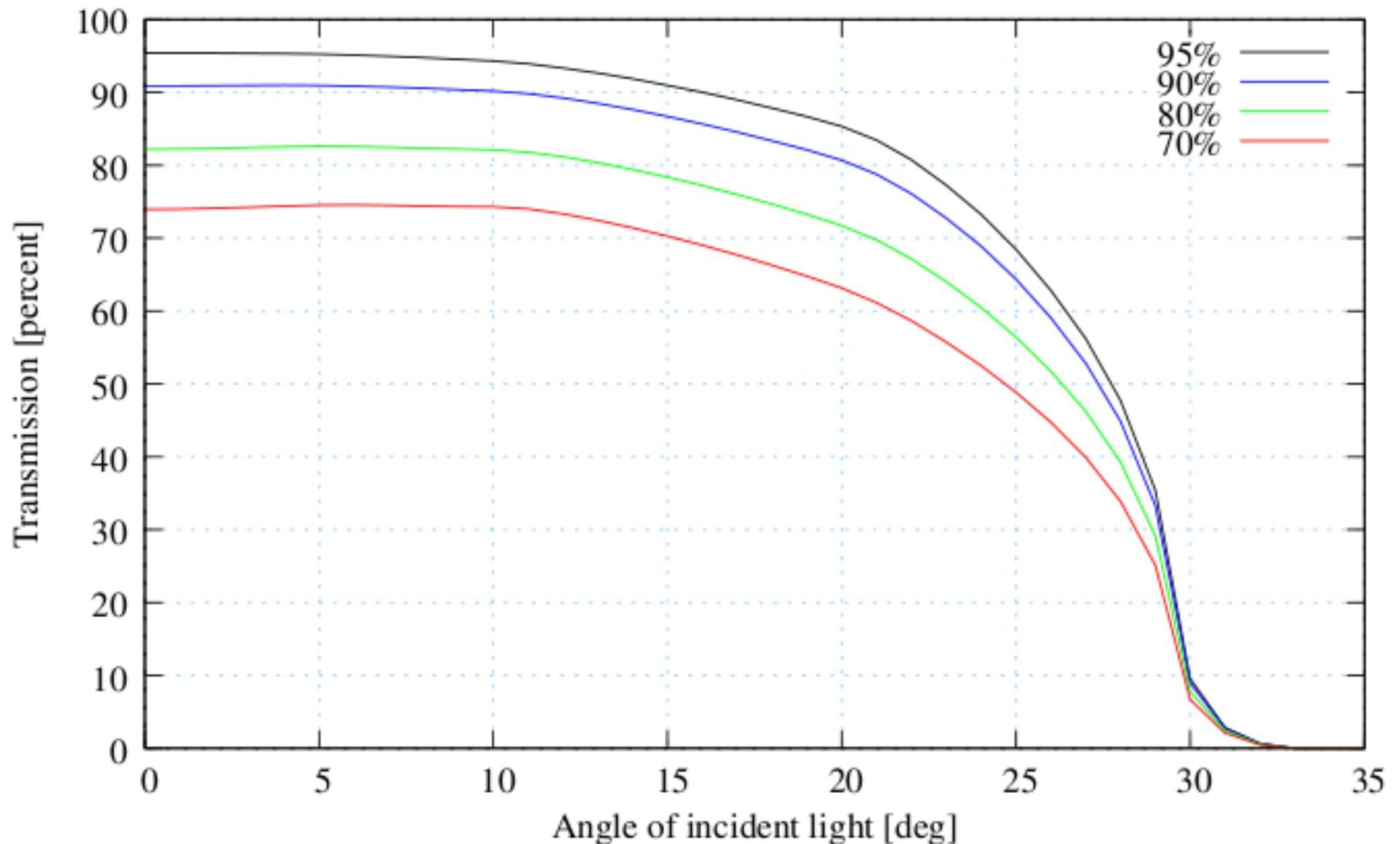
- Gamma, H, He, N, Fe
- 1/E powerlaw from 10 TeV (H: 5 TeV) to 5 PeV
- New production using Fluka planned

Detector simulation

Full detector simulation – sim_score [5]:

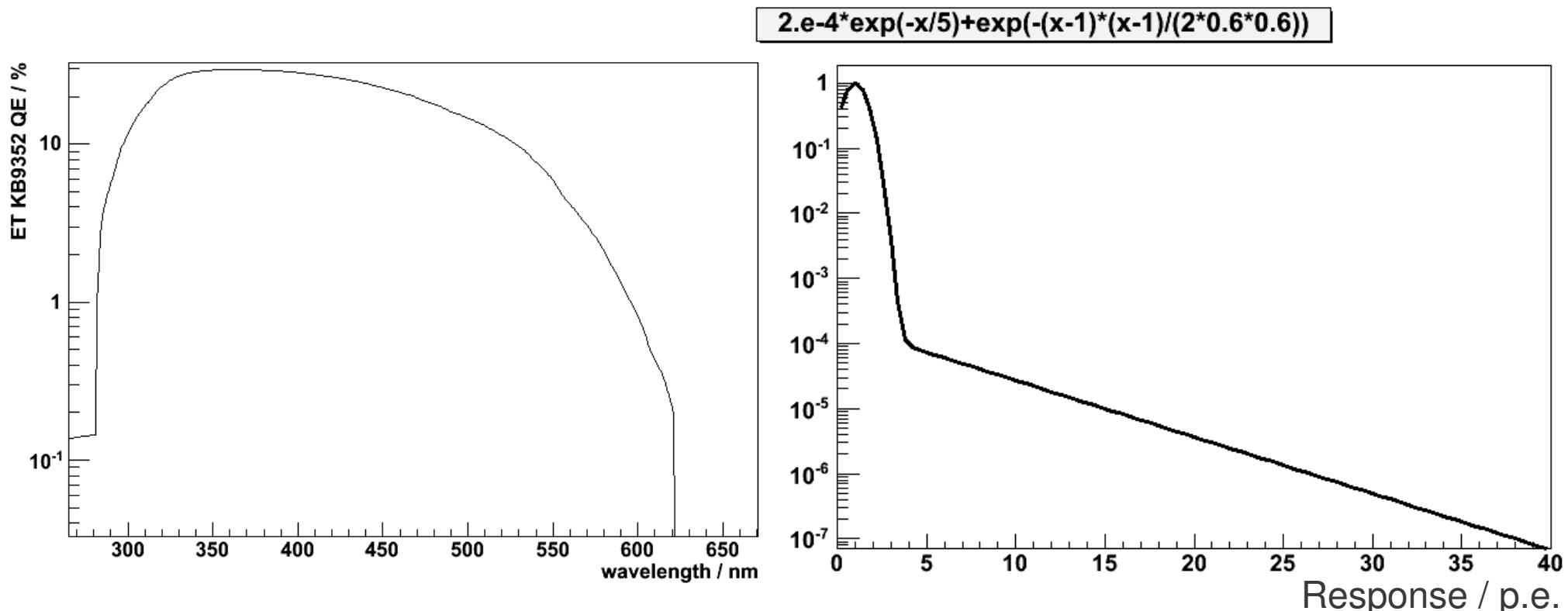
- Using iact package I/O routines, provided by [3]
- Winston cone acceptance included by ray-tracing simulation
- PMT quantum efficiency (Electron Tubes 8" PMT, data sheet)
- Electron collection efficiency
- PMT signal pulse-shape parameterization [4]
- Afterpulsing simulated w/ $P = 10^{-4}$ at 4 p.e.
- Local trigger: sum of 4 clipped channels
- Night-sky background (including pulse shaping), added to signals
- Array trigger: 1-station or 2-station NN (1 μ s coincidence window)

Winston cone acceptance

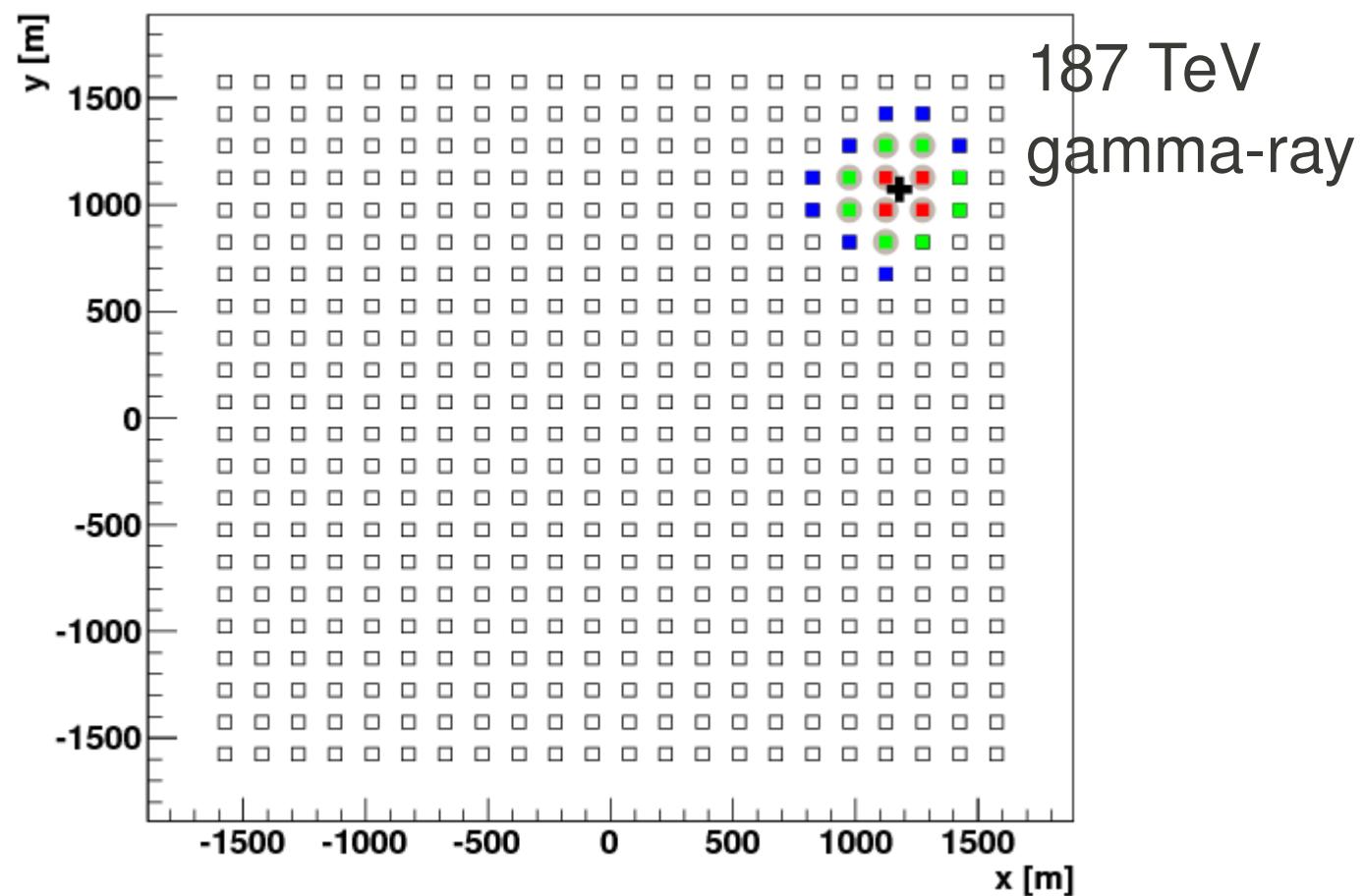


PMT simulation

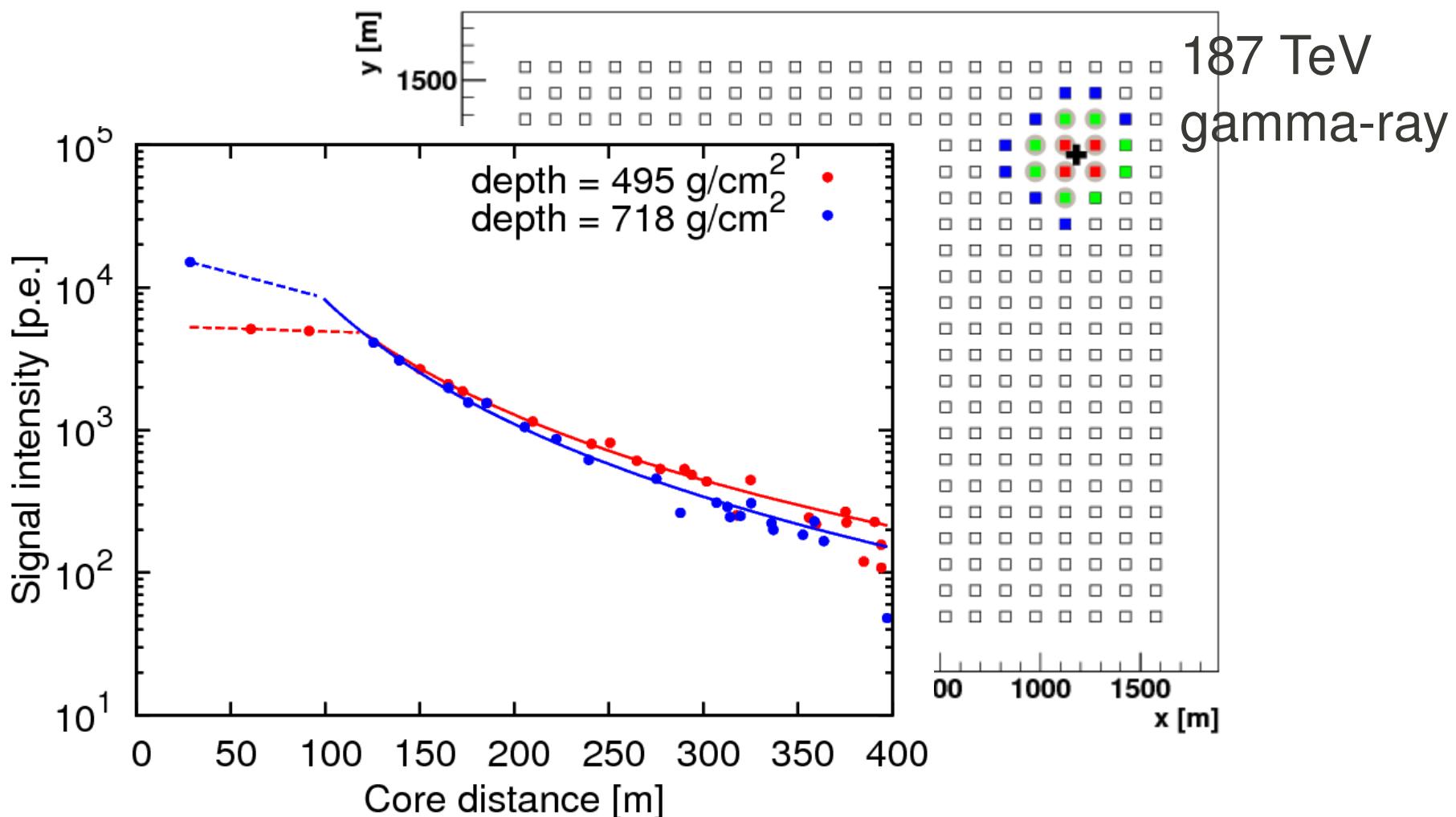
- Wavelength-dependent QE simulated
- Photomultiplier response including afterpulses



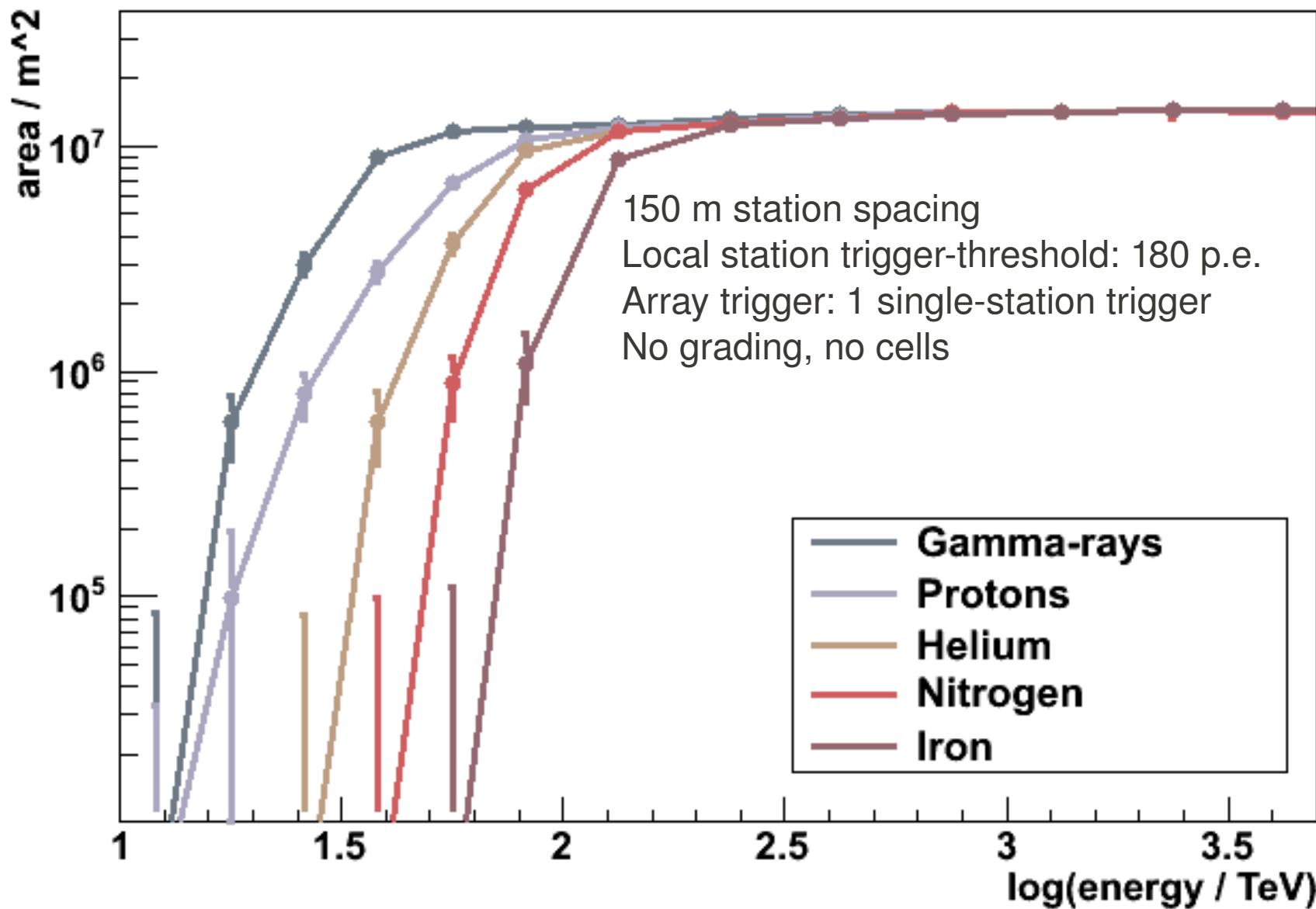
An event example



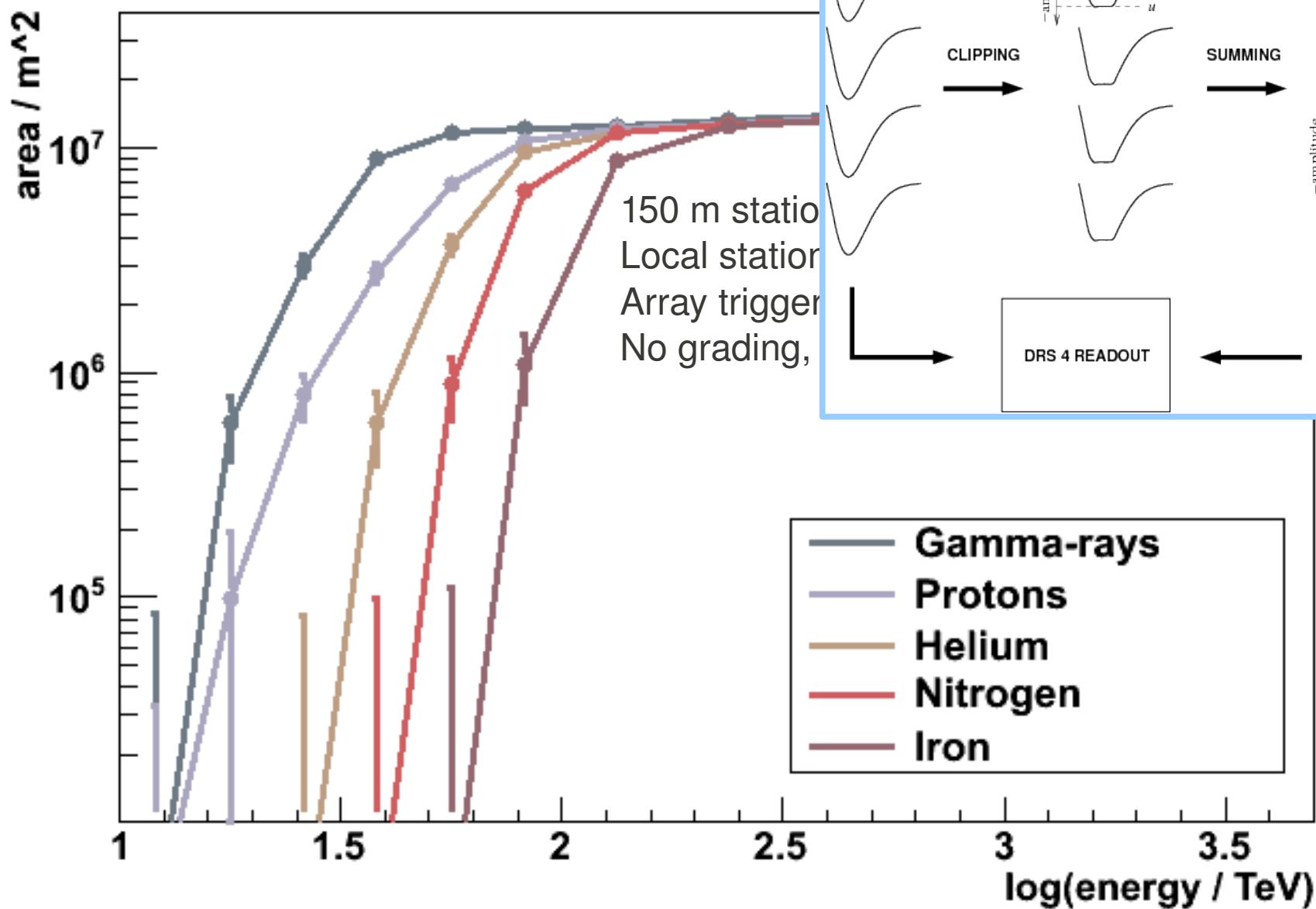
An event example



Effective CR trigger area



Effective CR trigger area

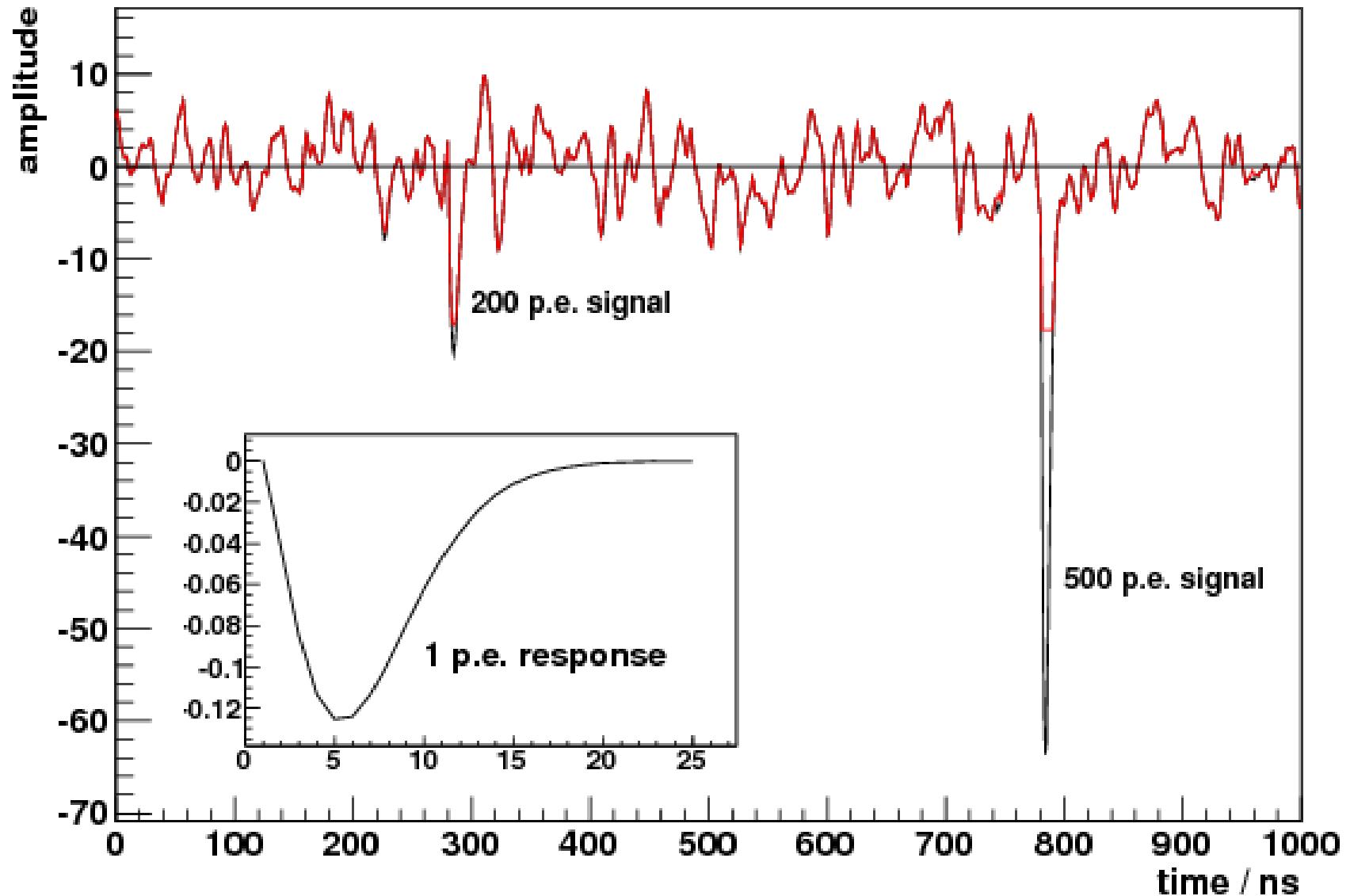


Expected night-sky background trigger rate

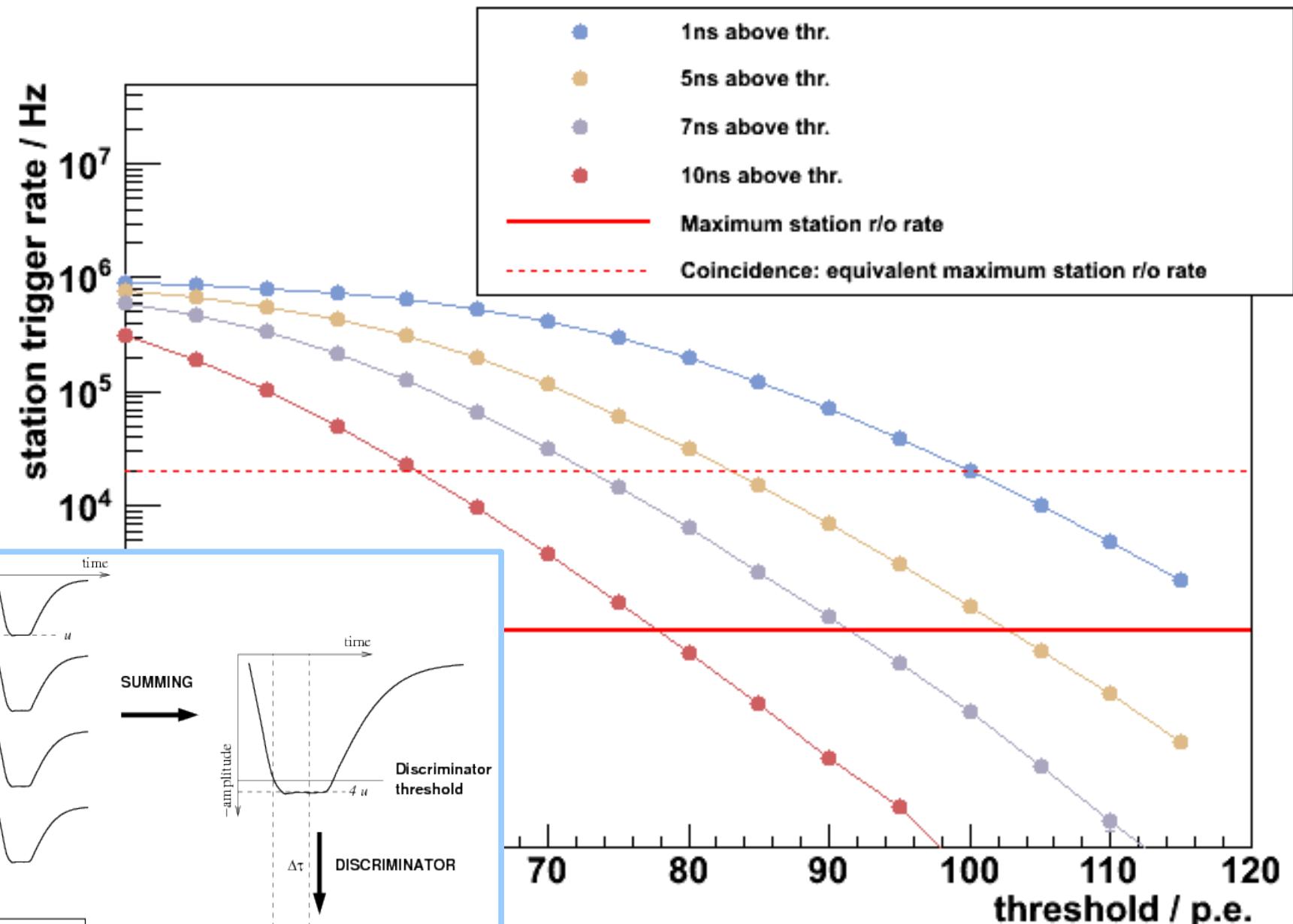
Separate NSB simulation, 4-channel station:

- NSB-rate from measurement in Australia [Hampf et al. 2010]
- Arrays of Photon times: equally distributed random numbers
- Pulse shaping + afterpulsing
- 4-channel coincidence trg:
 - channel-amplitude-clipping
 - analog sum of 4 clipped signals
 - discriminate sum
- Resulting **noise file**: 2s in 1ns bins
- Noise added segment-wise from file to simulated air-shower signal

Signal and noise

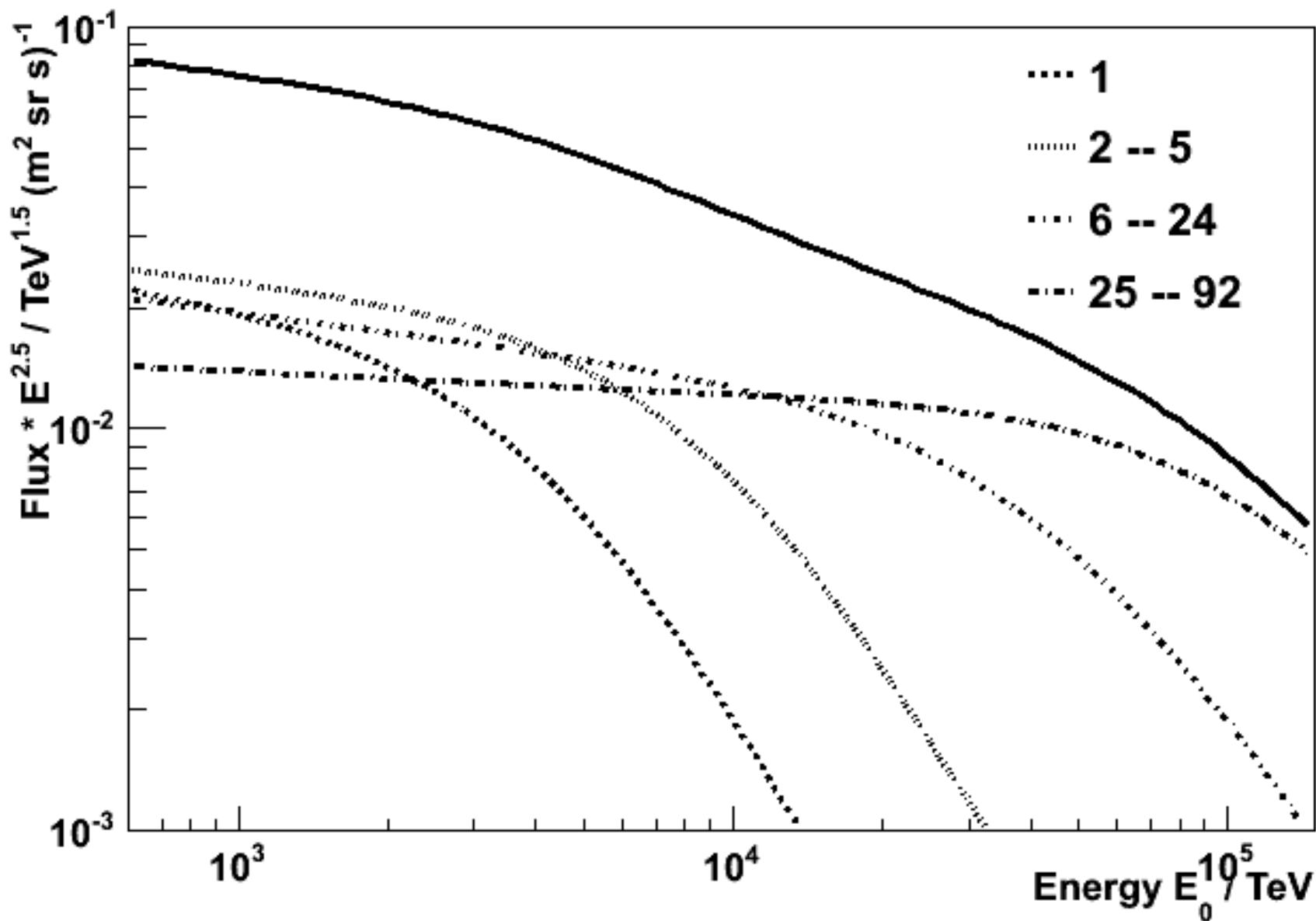


Expected night-sky background trigger rate



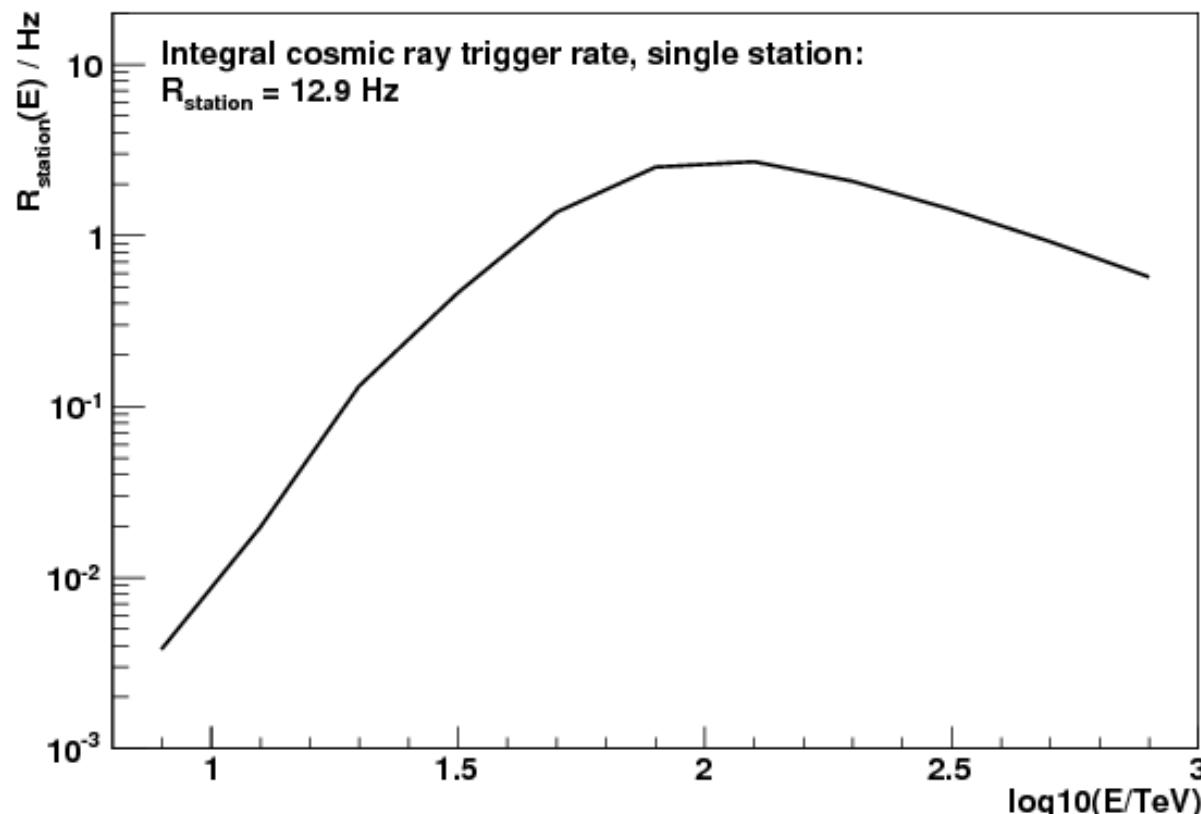
Hadron parametrization

Hoerandel 2003: polygonato model



Station hadron trigger rate

- Simulated average number of stations per bin
- Folding with polygonato model
- ~13Hz single station hadron trigger rate



Array hadron trigger rates

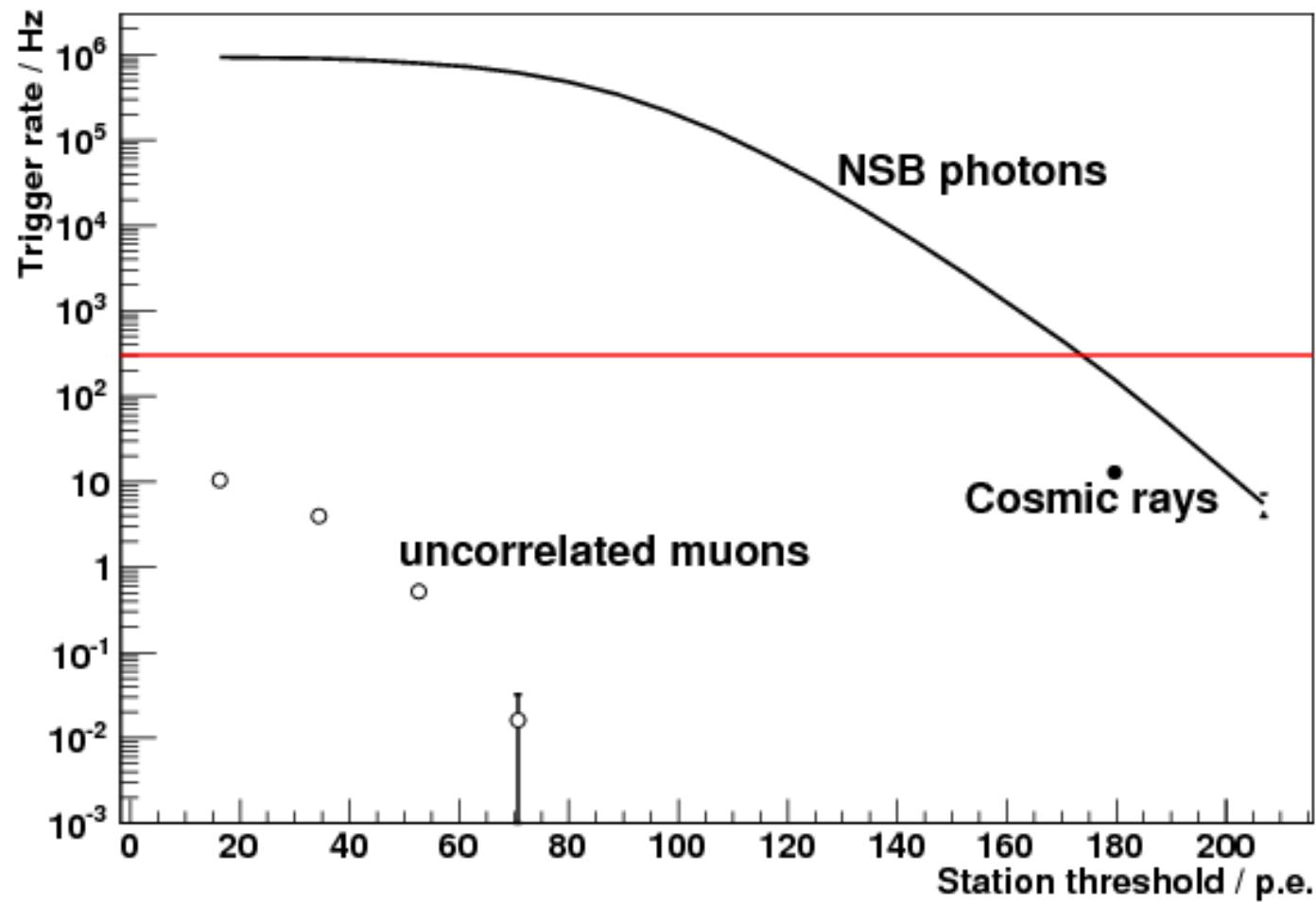
Trigger rates for $E > 10 \text{ TeV}$, before reconstruction cuts

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

Trigger condition: single station trigger

Proton	774 Hz
He	436 Hz
N	257 Hz
Fe	90 Hz
Array rate, all particles	$\sim 2 \text{ kHz}$
Single station rate	$\sim 13 \text{ Hz}$
NSB per station	< 300 Hz

Trigger rates summary



Shower core reconstruction

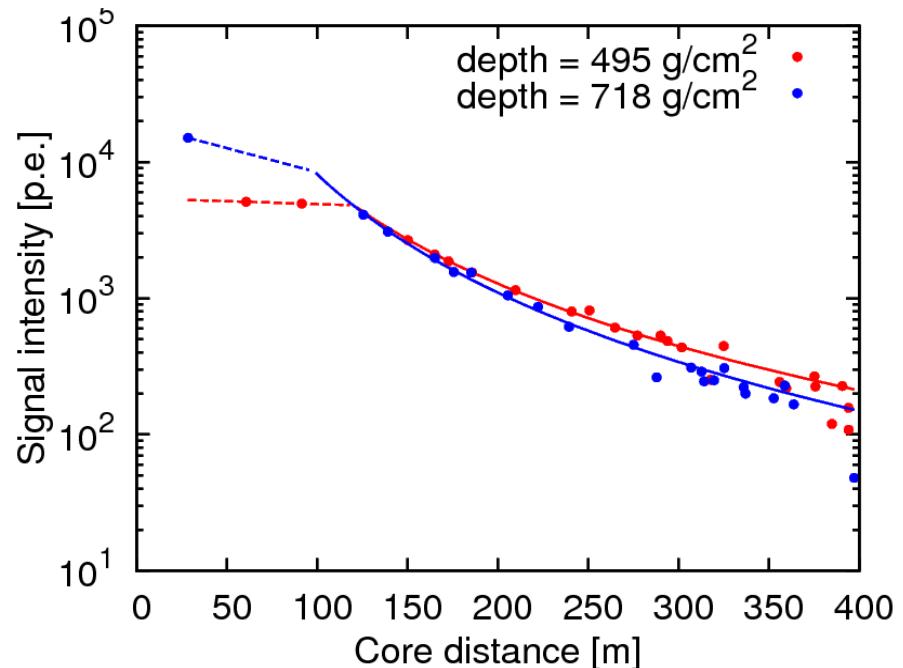
- Nstations < 5: weighted center of gravity
- Nstations ≥ 5 : Fit to LDF

$$\text{LDF}(r) = \begin{cases} P \exp(-d r) & \text{for } r < c_{LDF} \approx 120 \text{ m} \\ Q r^k & \text{for } r > c_{LDF} \end{cases}$$

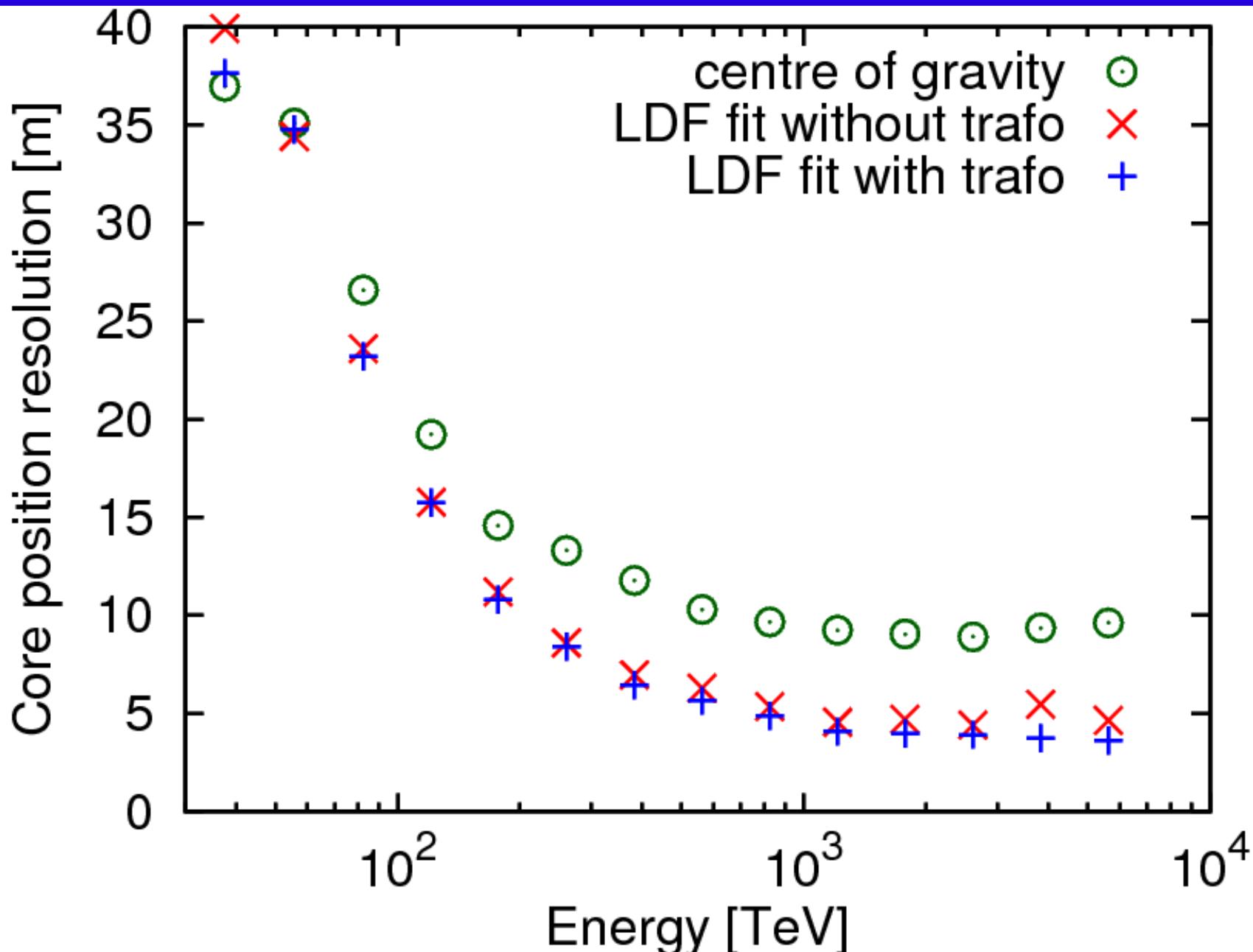
$$r = r(x, y) = \sqrt{x^2 + y^2}$$

$$Q = \frac{P \exp(-d c_{LDF})}{(c_{LDF})^k}$$

- Free parameters P, d, k, (x,y).
Nstations ≥ 6 : c_{LDF} free parameter
- To come:
use width for outside showers



Shower core resolution



Direction reconstruction

- >3 stations: model fit adapted from Stamatescu et al. 2008,
Parametrization of time-delay dt at detector position

$$dt(k, z) = \frac{1}{c} \left(\sqrt{k} - \frac{z}{\cos(\theta)} + \frac{8.0}{z} \sqrt{k} \eta_0 \left(1 - \exp \left(\frac{-z}{8.0} \right) \right) \right)$$

$$k(r, z) = r^2 + z^2 \frac{1}{\cos(\theta)^2} + 2 r z \tan(\theta) \cos(\delta)$$

$$\delta = \phi + \text{atan2}((x_{\text{Det}} - x_{\text{core}}), (y_{\text{Det}} - y_{\text{core}}))$$

Direction reconstruction

- >3 stations: model fit adapted from Stamatescu et al. 2008,
Parametrization of time-delay dt at detector position

**r: Distance from shower
core to detector**

**Slope of
atmospheric
refractive index**

Shower height in km

$$dt(k, z) = \frac{1}{c} \left(\sqrt{k} - \frac{z}{\cos(\theta)} + \frac{8.0}{z} \sqrt{\kappa \eta_0} \left(1 - \exp \left(\frac{-z}{8.0} \right) \right) \right)$$

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**Zenith
angle**

Direction reconstruction

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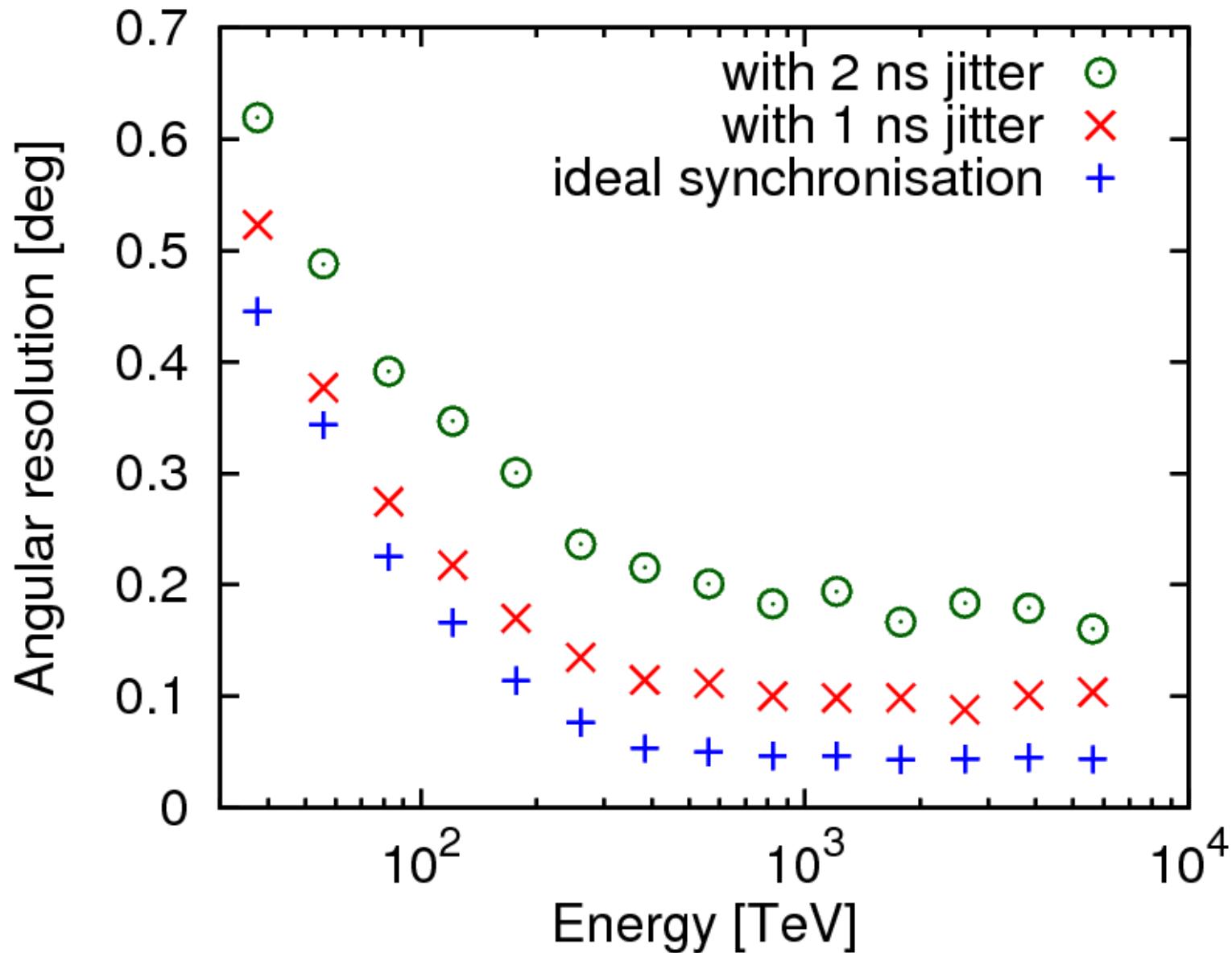
Free parameters: height & direction

Results in good angular reconstruction
And rough 1st order shower max. estimation

**Slope of
atmospheric
refractive index**

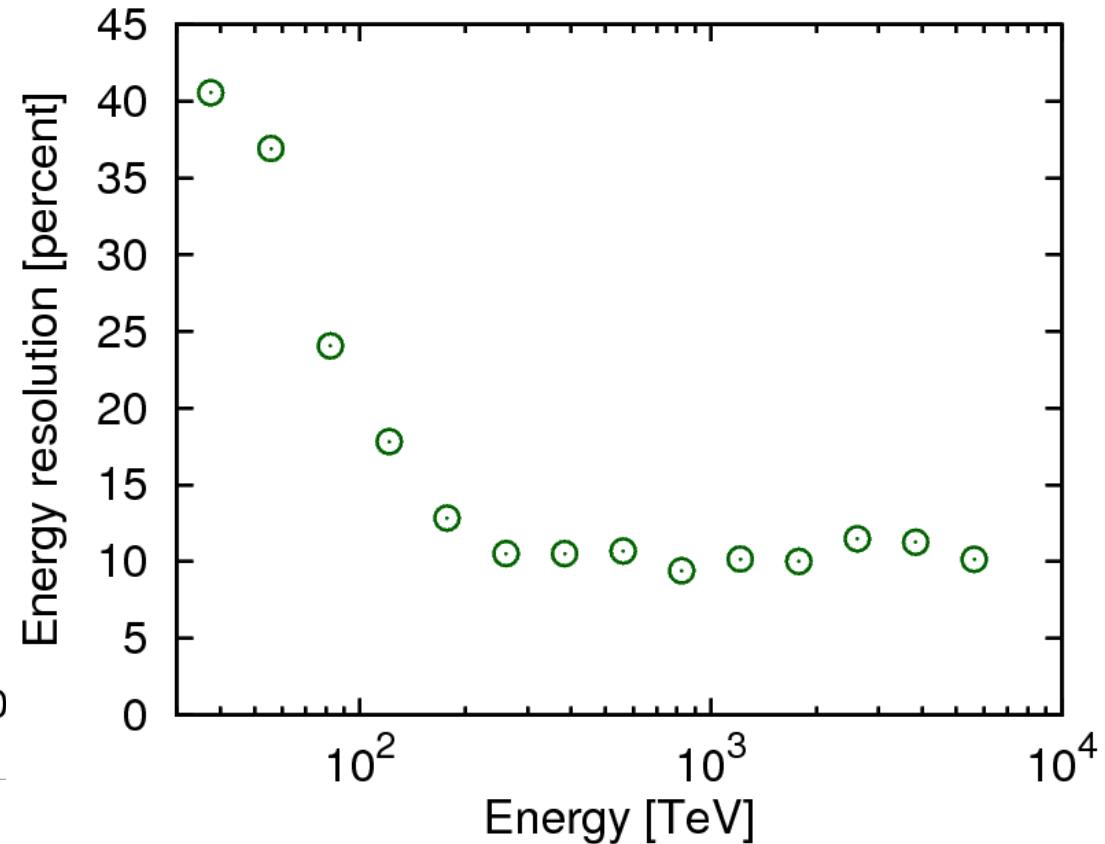
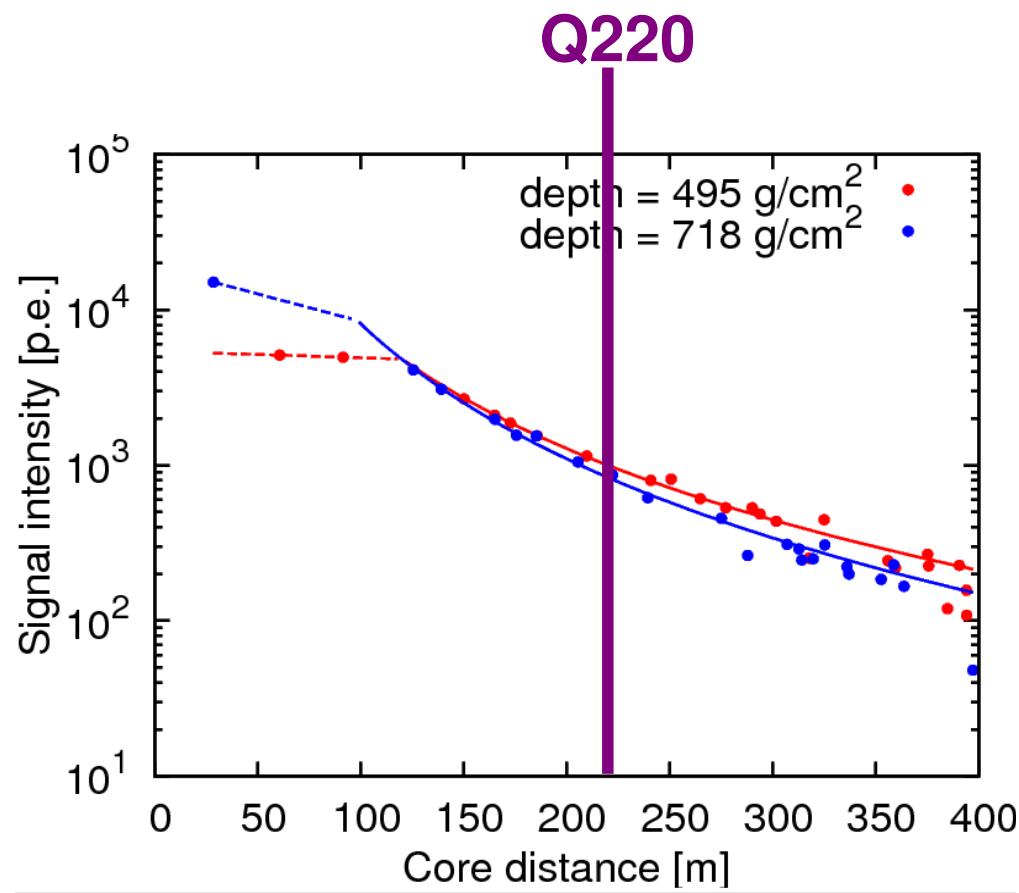
**Zenith
angle**

Angular resolution



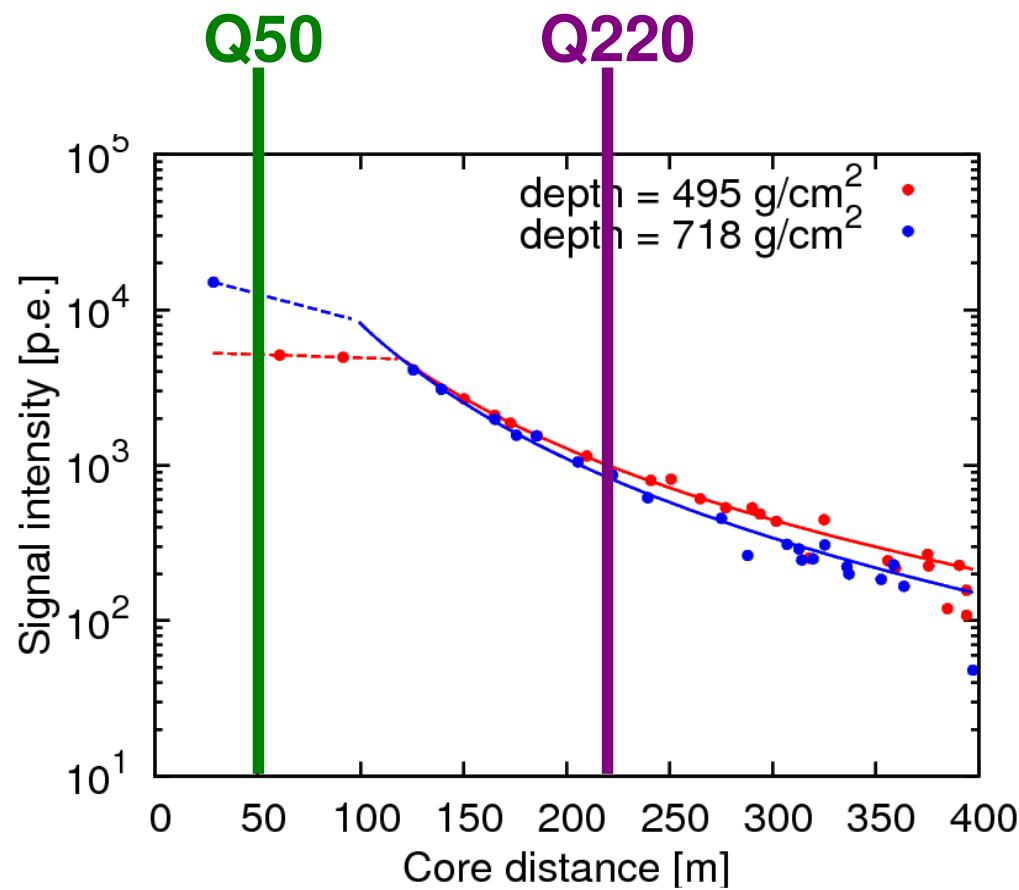
Energy reconstruction

- Smallest impact of shower depth on photon density at 220m

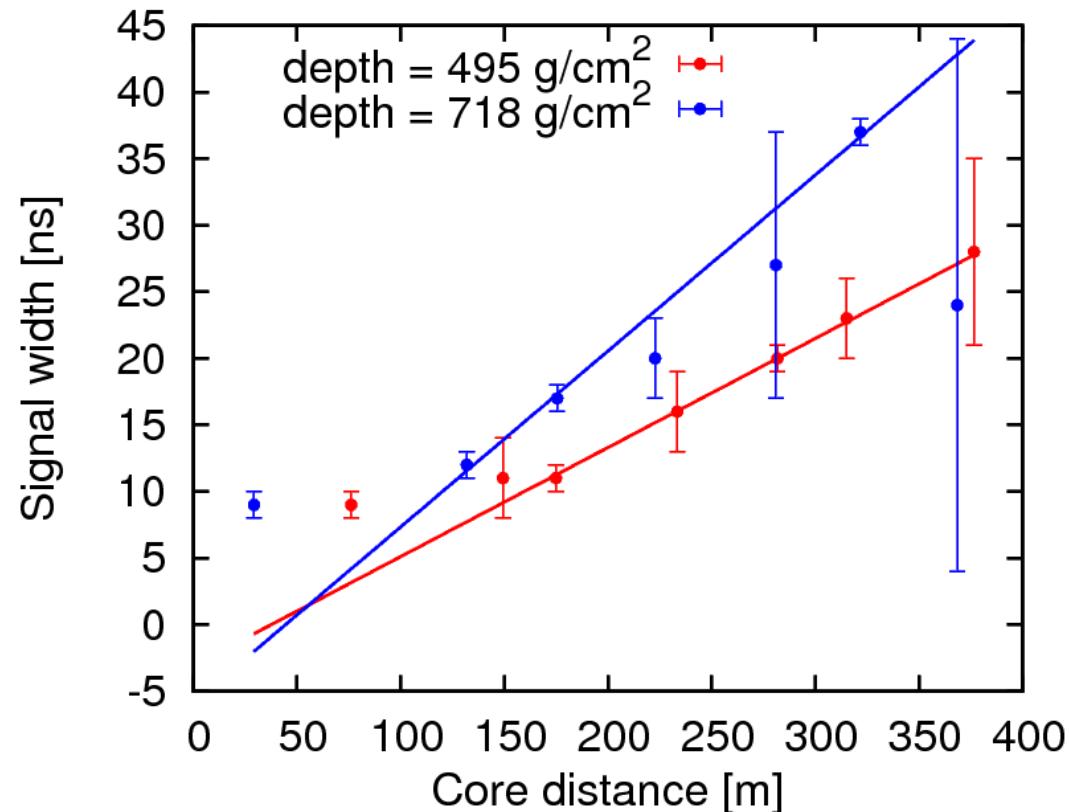


Shower depth reconstruction

- **D_s:**
Depth from LDF slope, Q50/Q220

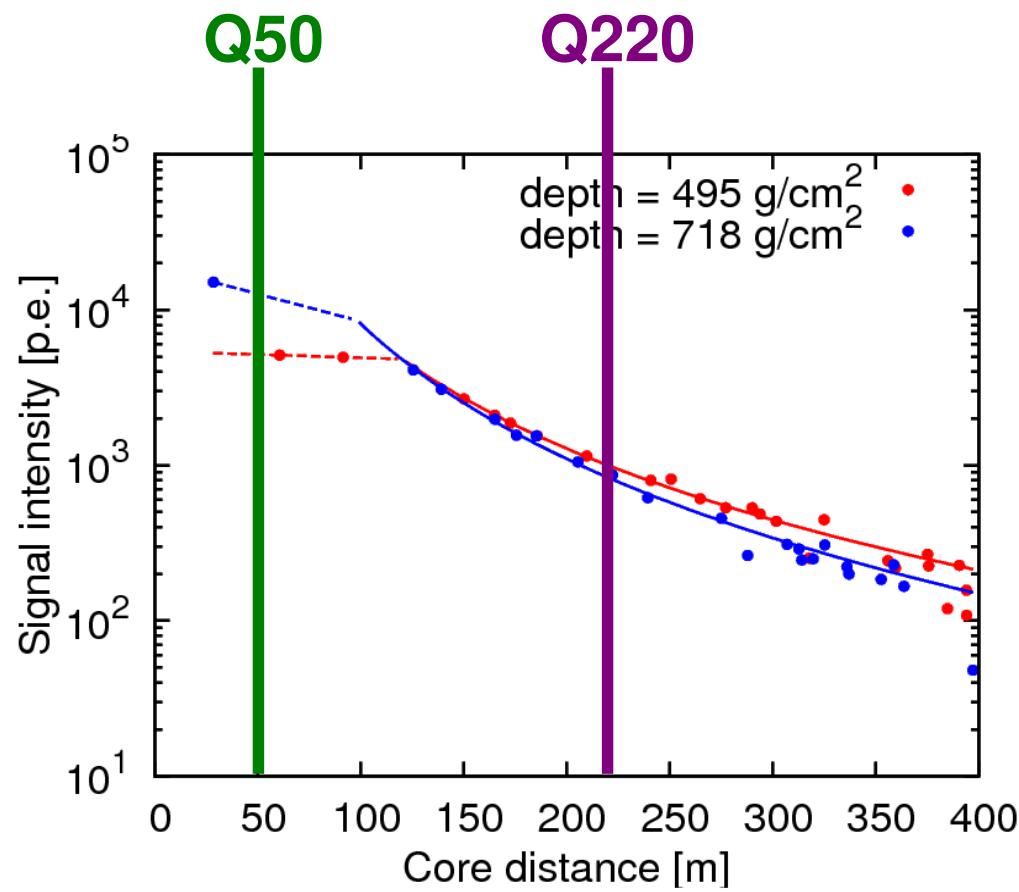


- **D_w:** Depth from signal width
- signal-stacking: add signals with same core-distance
- effective at core-distance > 150m

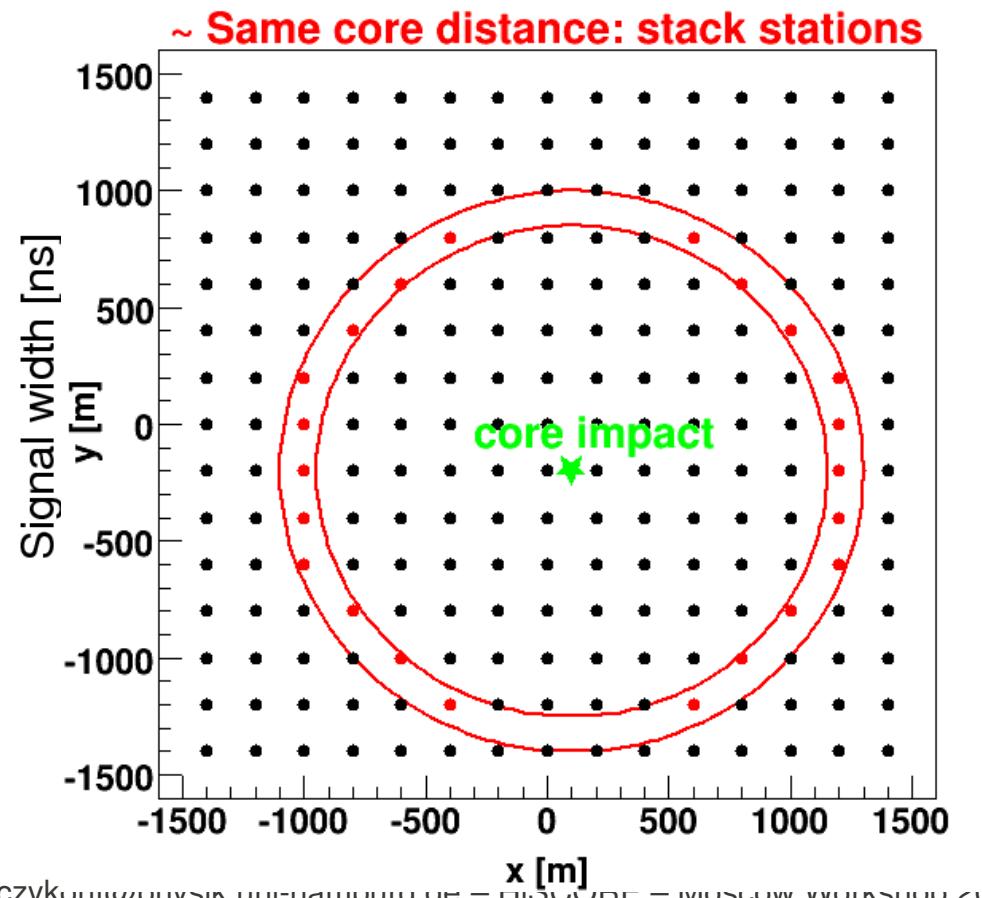


Shower depth reconstruction

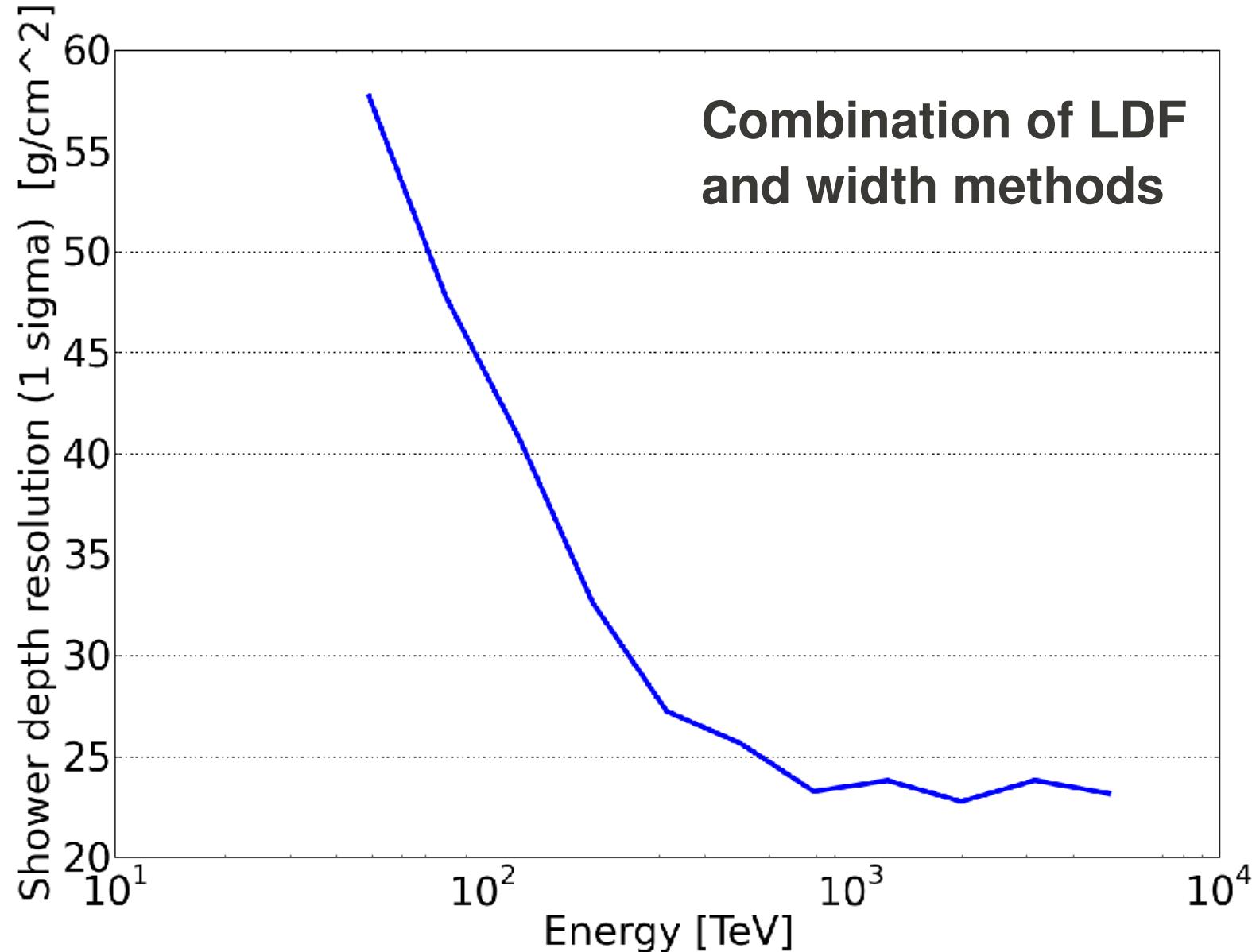
- Ds:
Depth from LDF slope: Q_{50}/Q_{220}



- Dw: Depth from signal width
- signal-stacking: add signals with same core-distance



Shower depth resolution

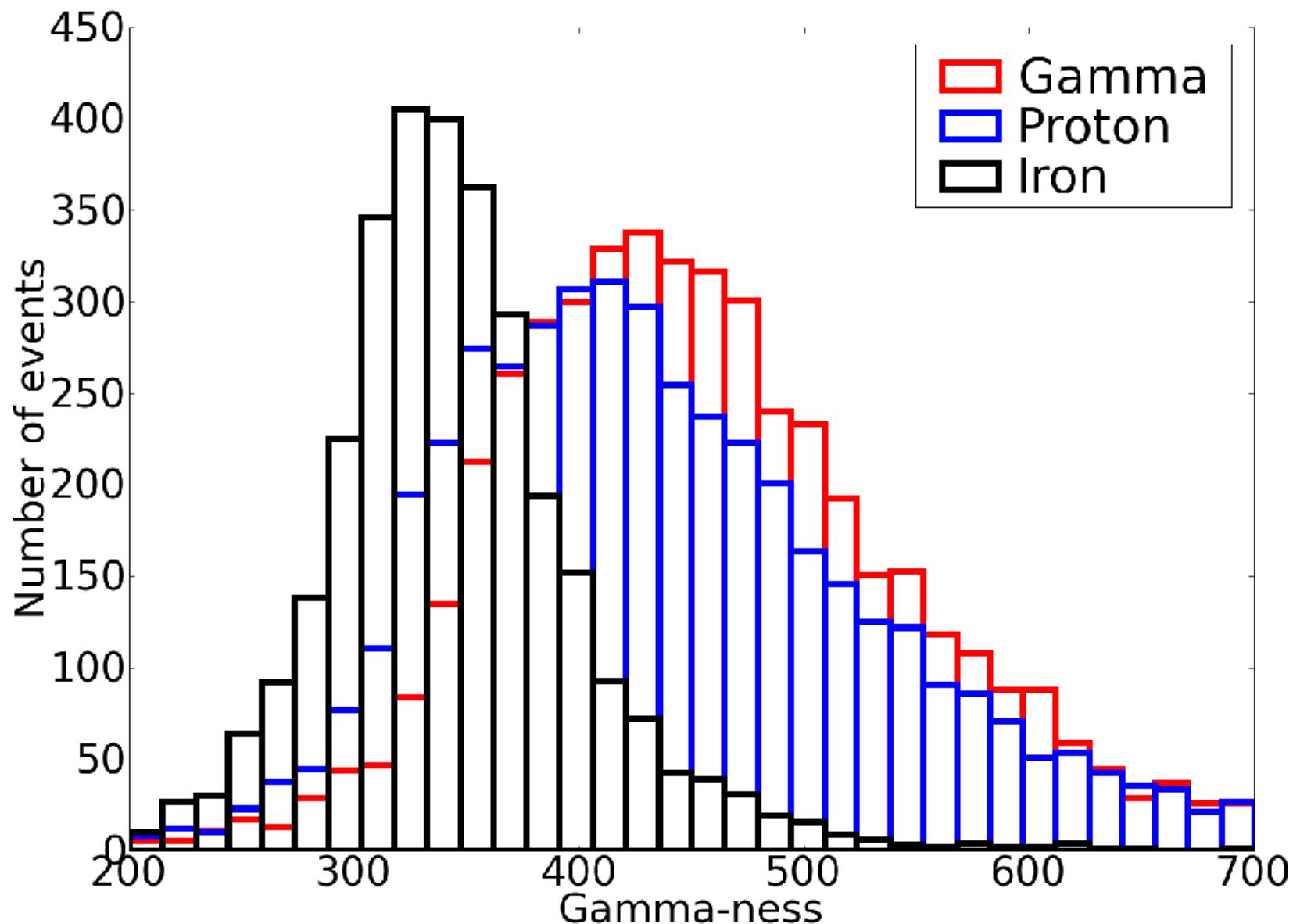


Particle identification

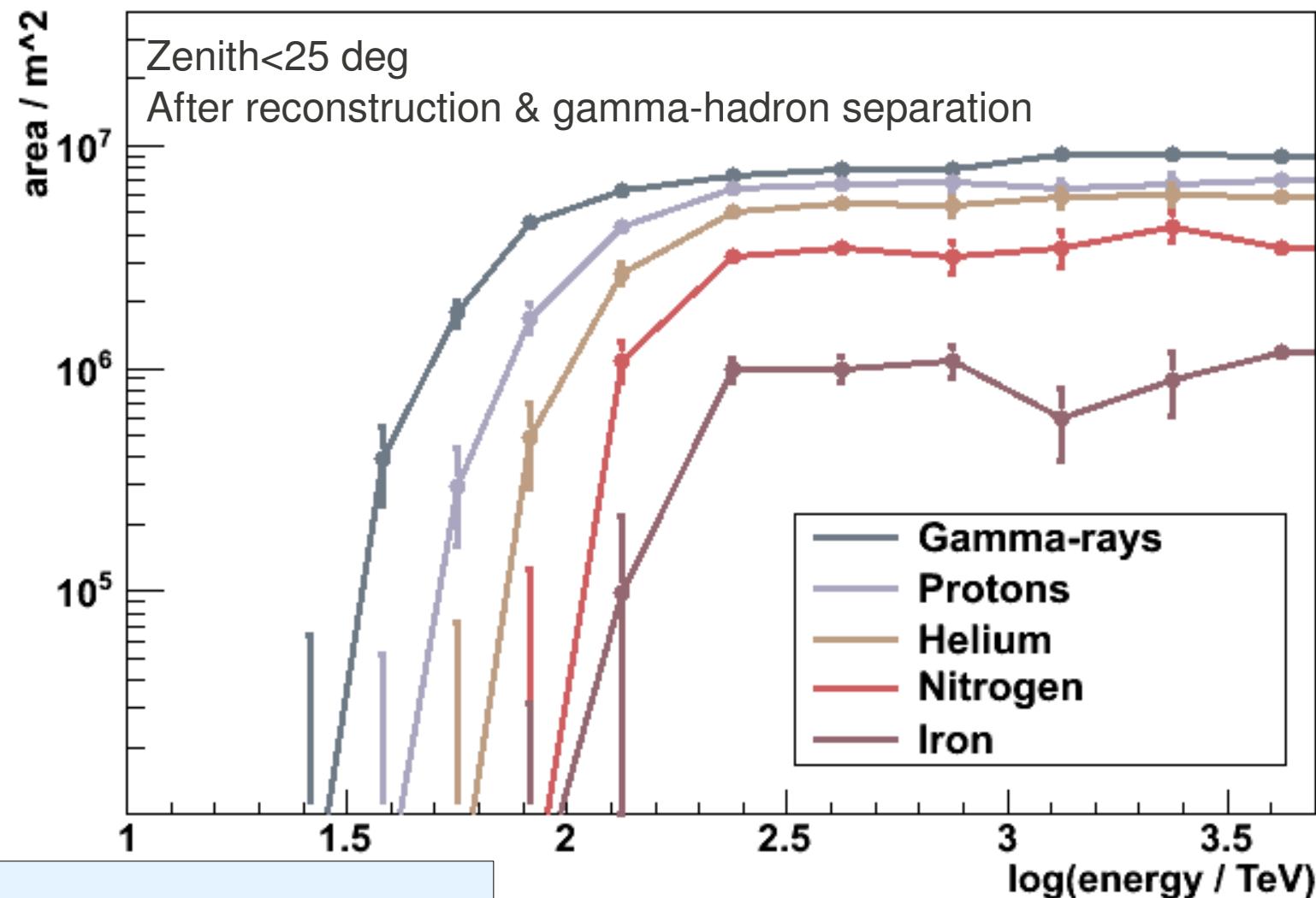
- Gamma-hadron separation
 - Cosmic ray composition
- 1) Shower depth depends on particle type
 - 2) The signal width also depends on particle type
 - Systematic shift of depth estimate Dw
 - Separator: Dw/Dq

Combination of 1) and 2) → gamma-ness parameter

Particle identification



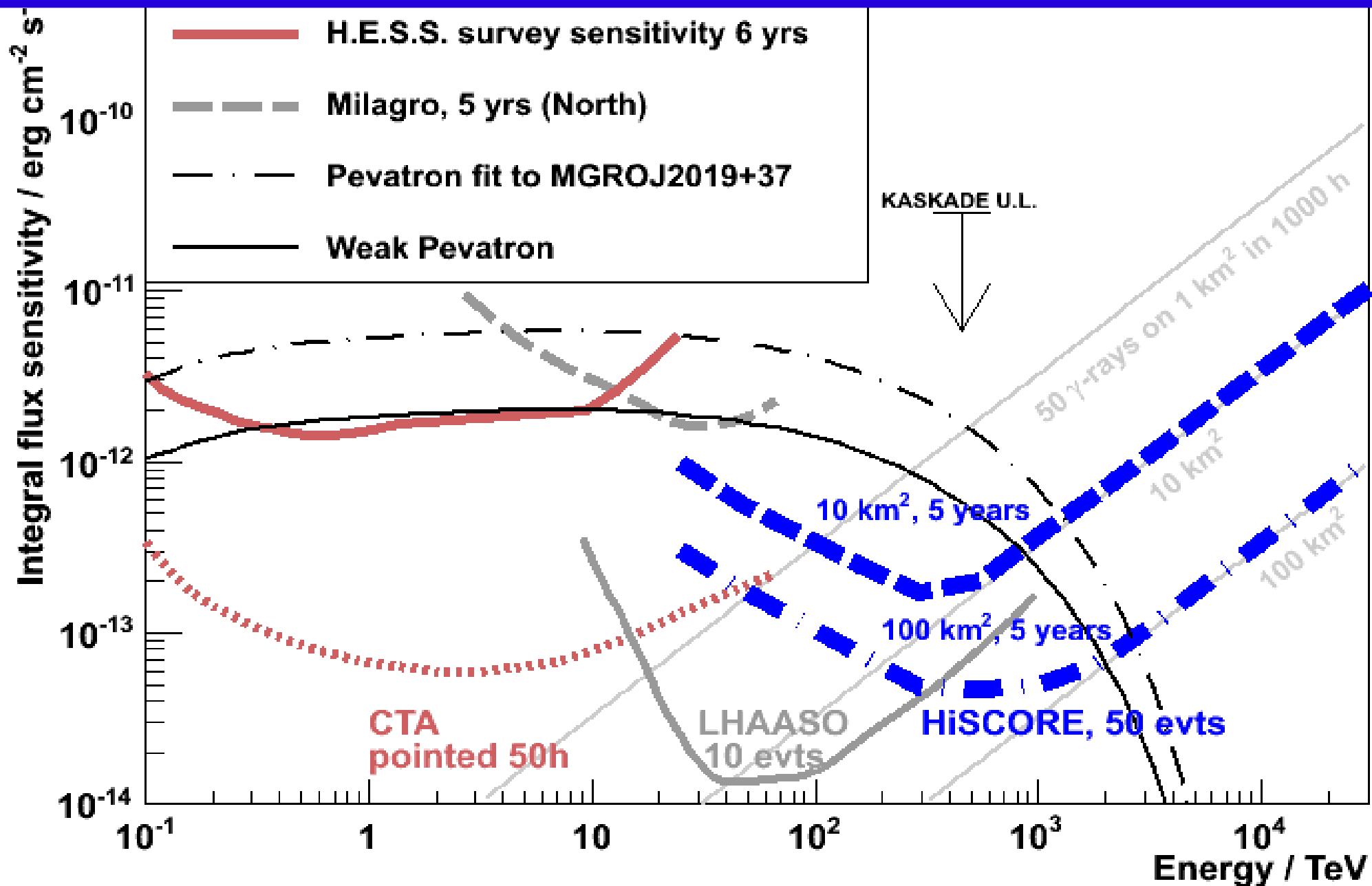
Effective area @ reconstruction level



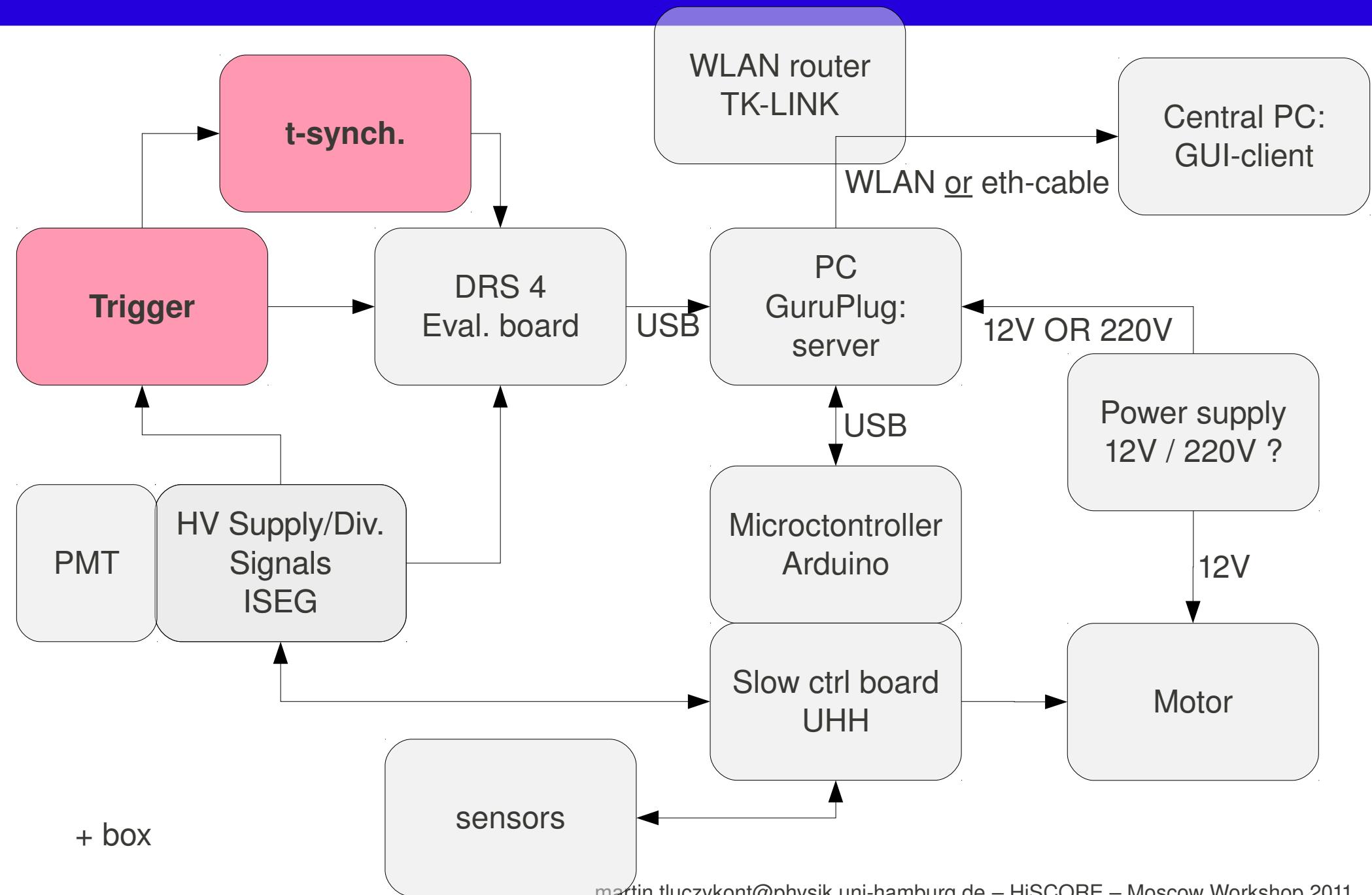
Reconstruction cuts:

- ≥ 3 triggered stations
- Contained reconstructed core impact position
- Separator ≥ 400

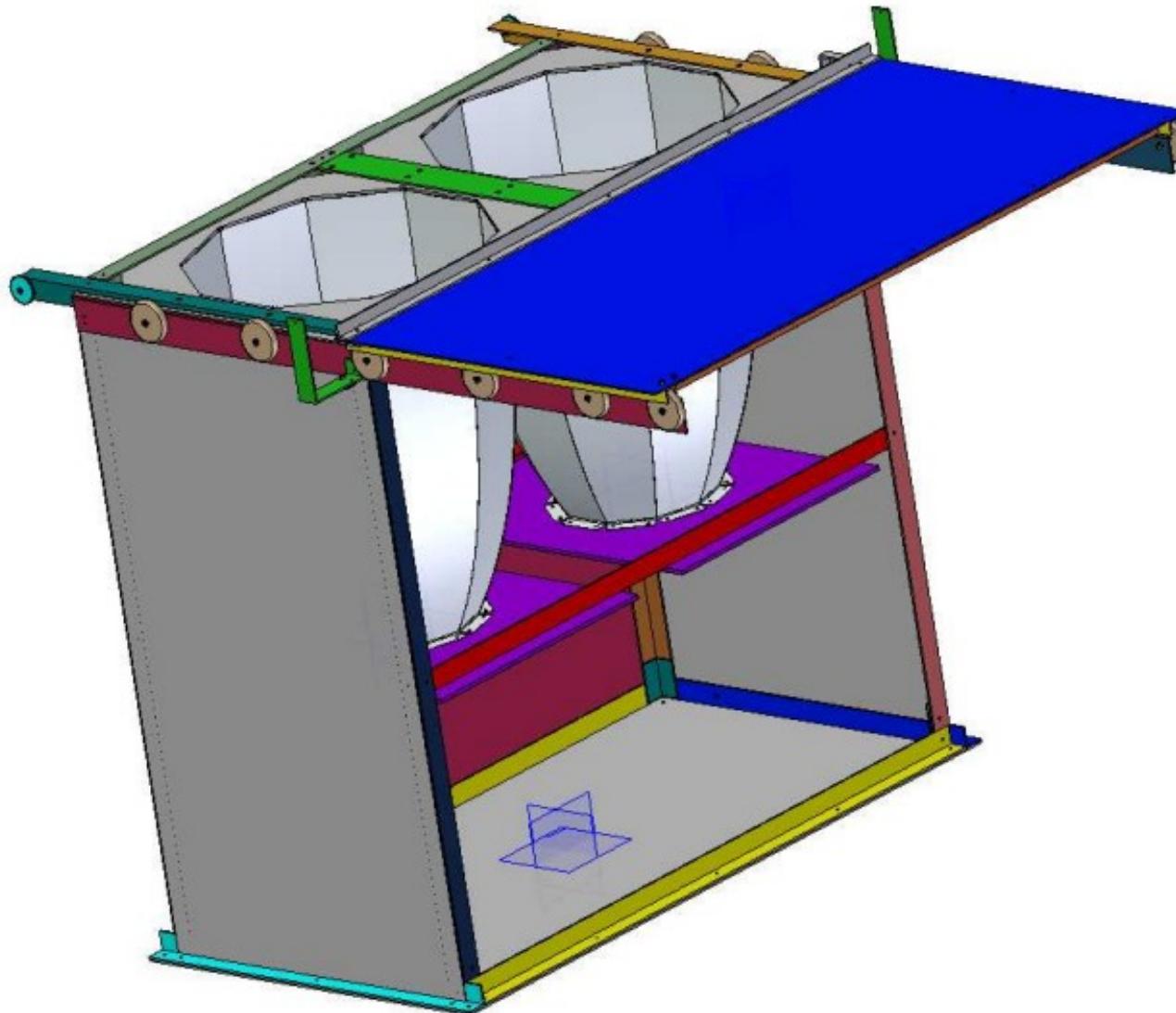
SCORE Sensitivity



Hardware status



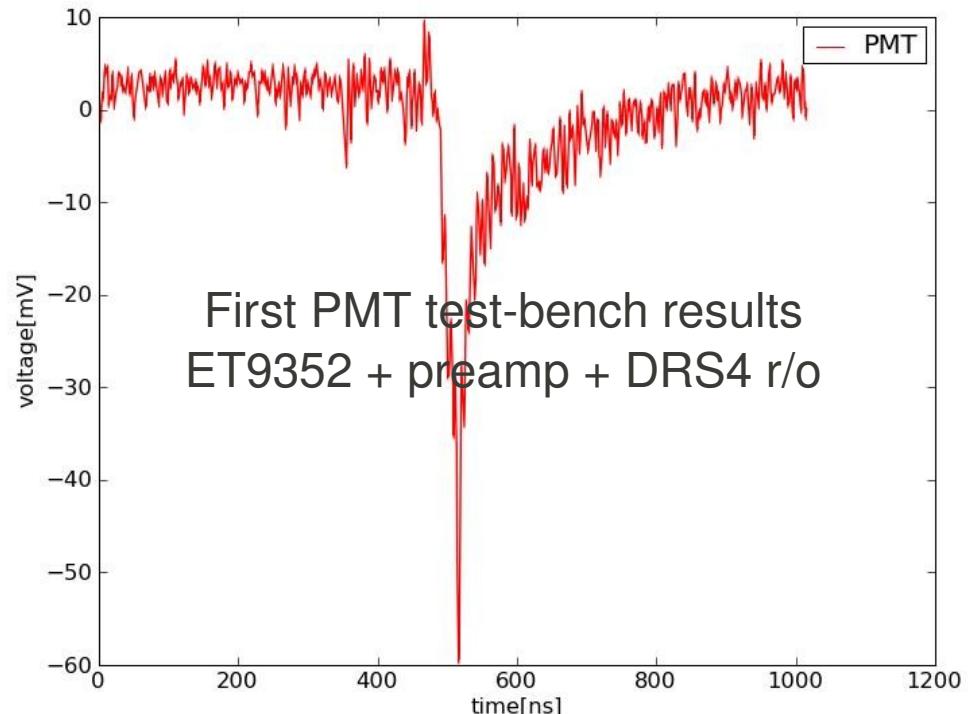
Mechanics



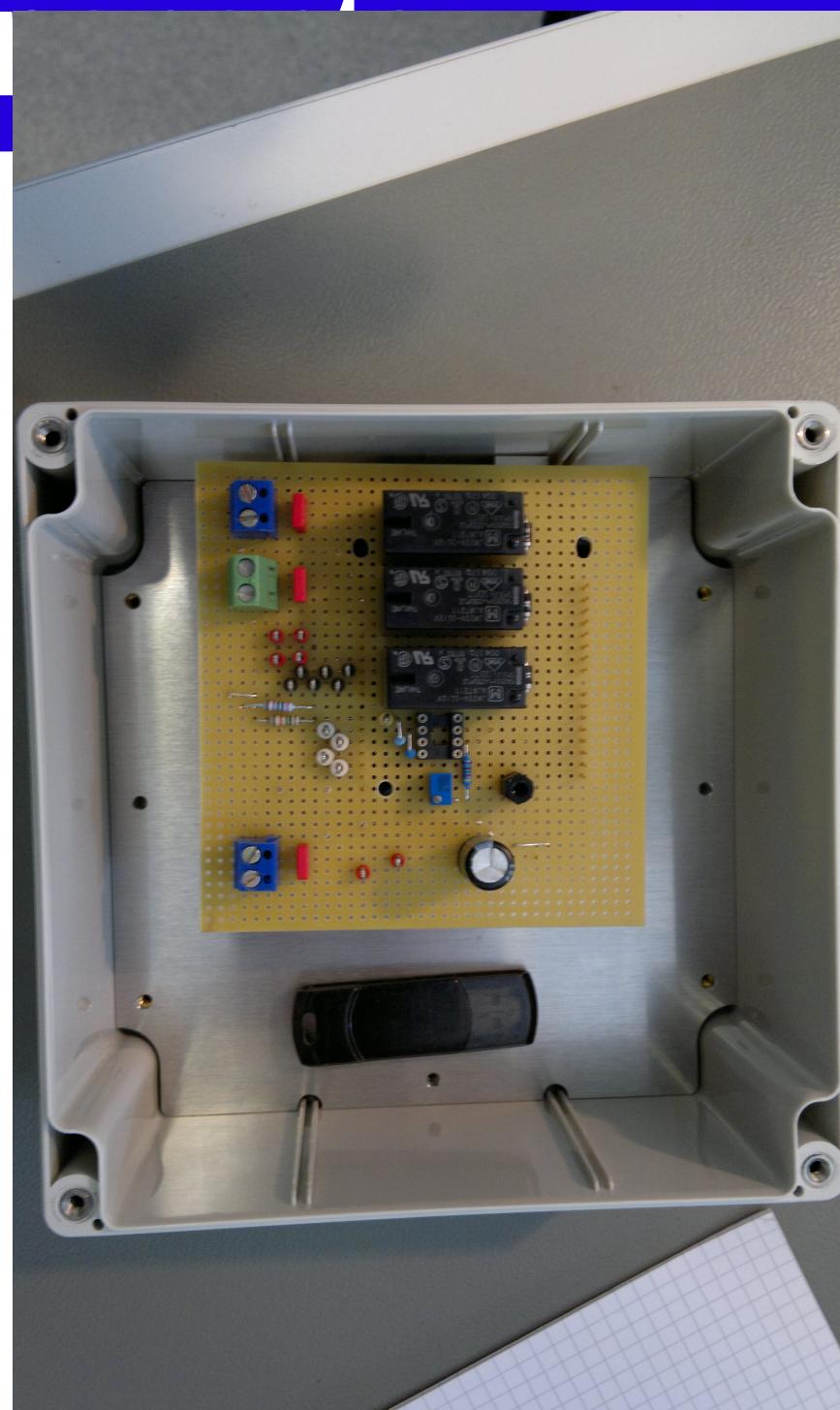
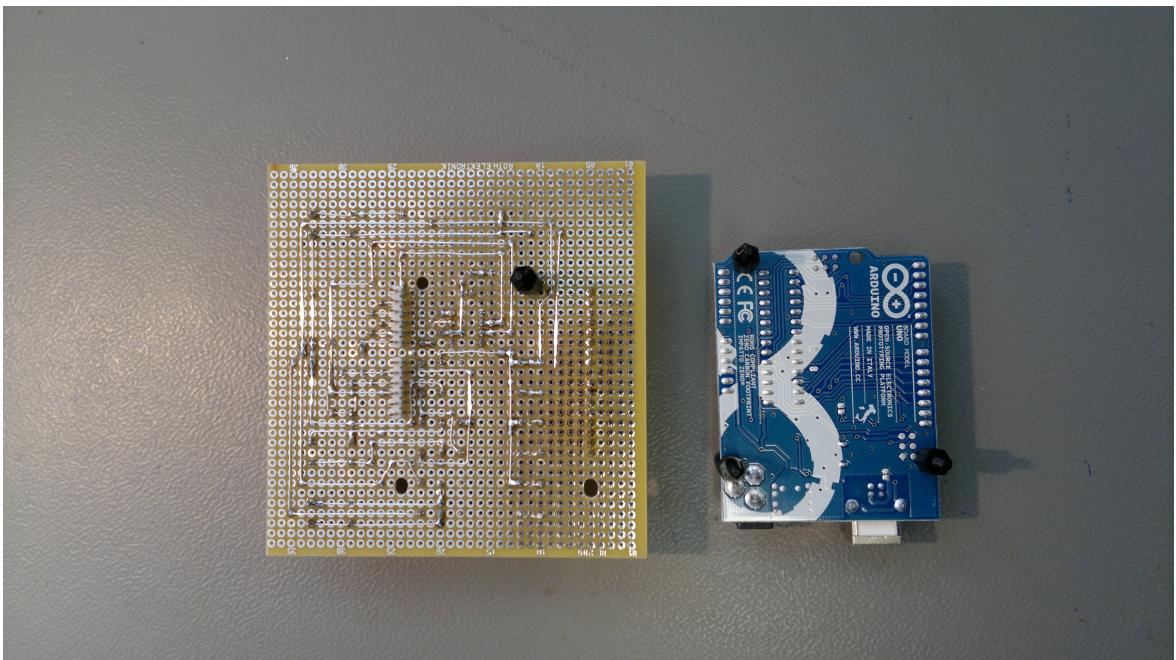
Status & current activities



Winston cone prototype:
“Barrel-mounting” method
Plan: use UP4300 refl. foil

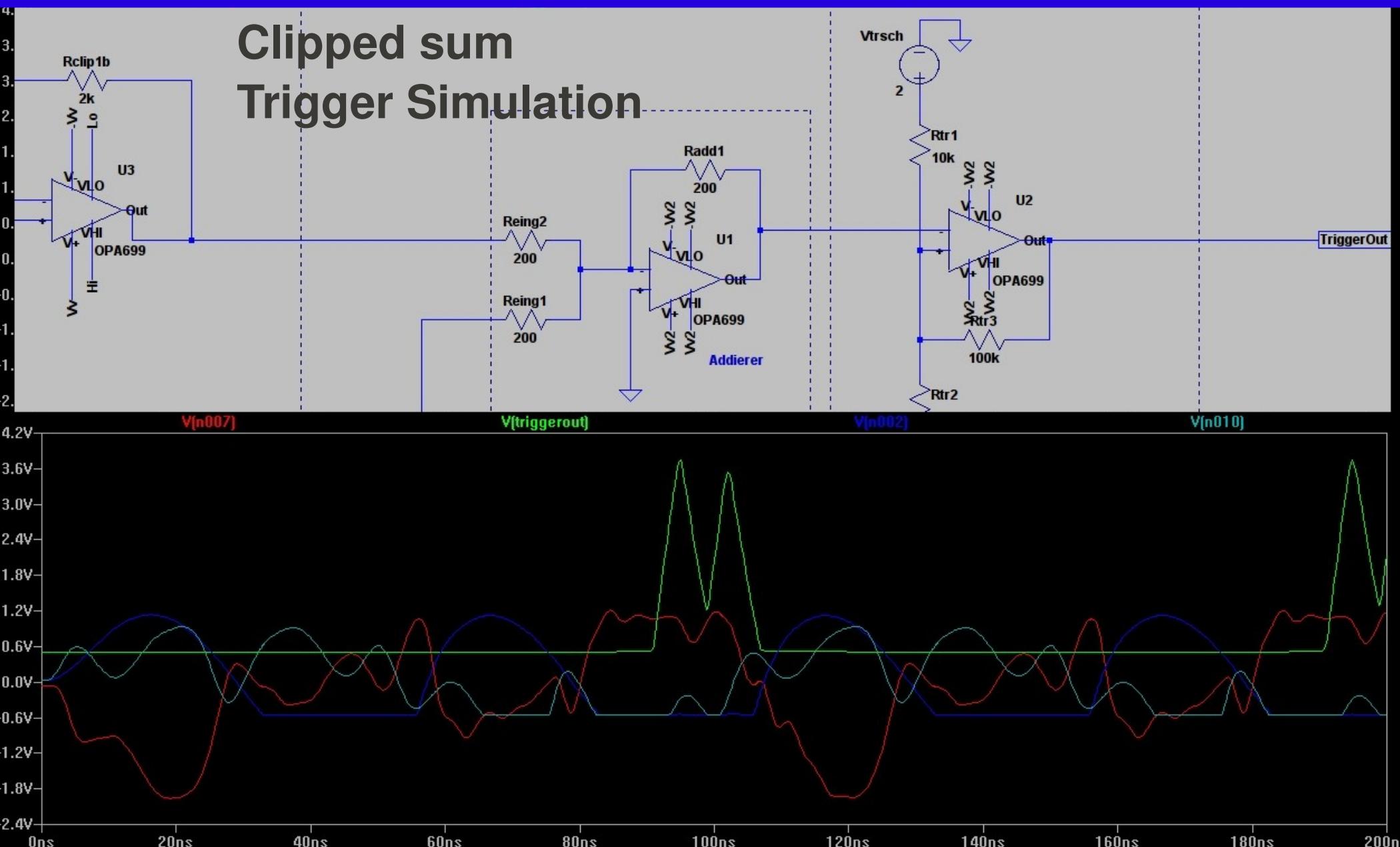


Available components



Available components

Clipped sum Trigger Simulation



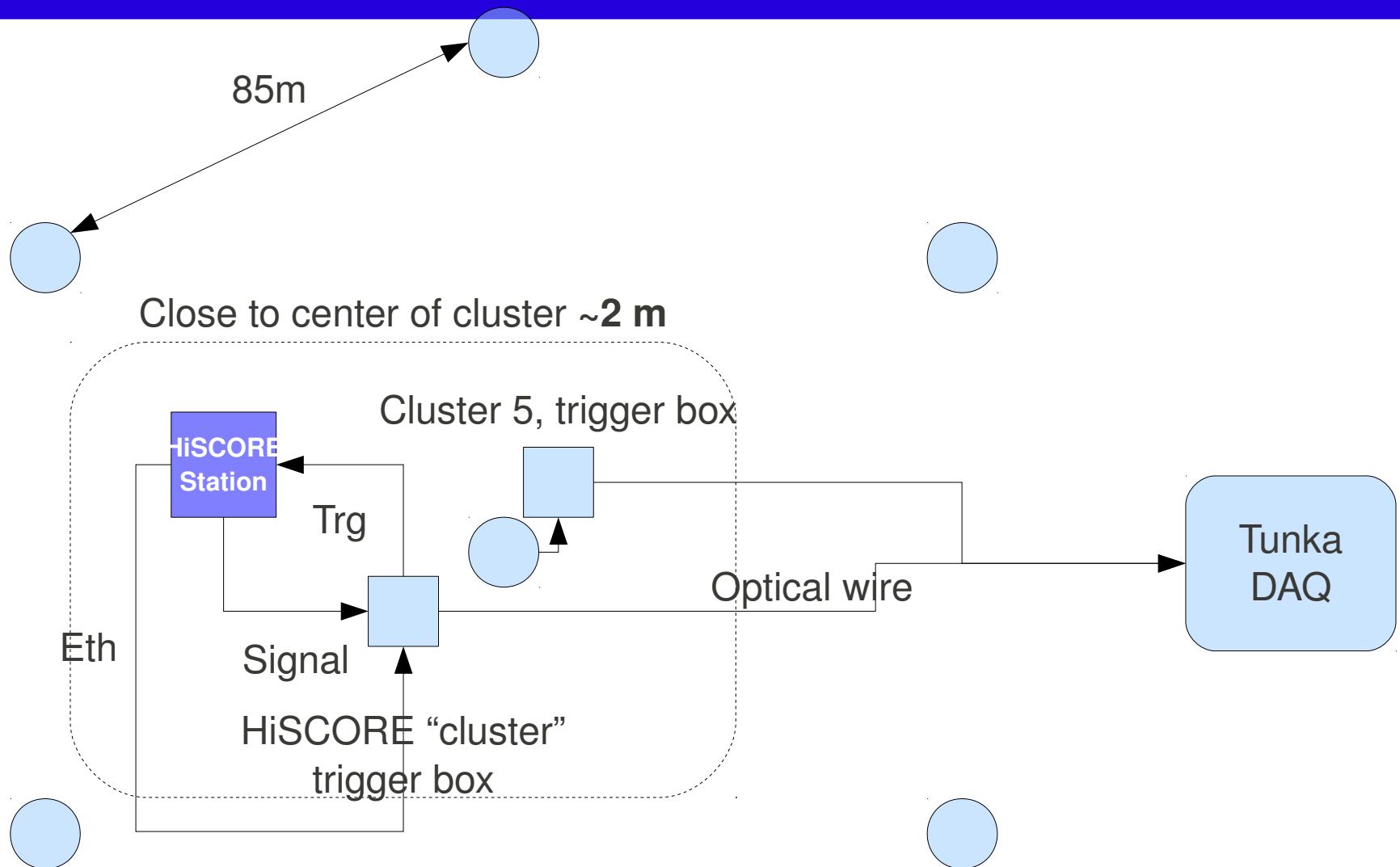
Available components summary

component	status	plan
PMT	Available / tested	Await further delivery Test Hamamatsu PMTs
DRS4 R/O	Available / tested	
HV sup/div	Available / tested	
PlugPC	Available / tested	
Microcontroller	Available / tested	
SlowCtrl board	Developed / partly tested	Await full board this week
Sensors	Available / tested	
Trigger	Concept ready To be developed	Fall-back: internal DRS4 trigger
GUI-client / server connection	Available / partly tested	Further development Full test with all station components @ UHH

HiSCORE prototype at TUNKA

- Deployment of 1 prototype station in 2011
- 2+ in 2012
- Cross-calibration with TUNKA Cherenkov
- Potential of joint operation with muon detectors
- Synergies with radio detectors
- 2011: use TUNKA trigger / DAQ
- 2012: HiSCORE local trigger
- 2012+: start deployment of engineering array for proof of principle and first physics
- New CORSIKA+sim_score production for TUNKA site, including FLUKA usage

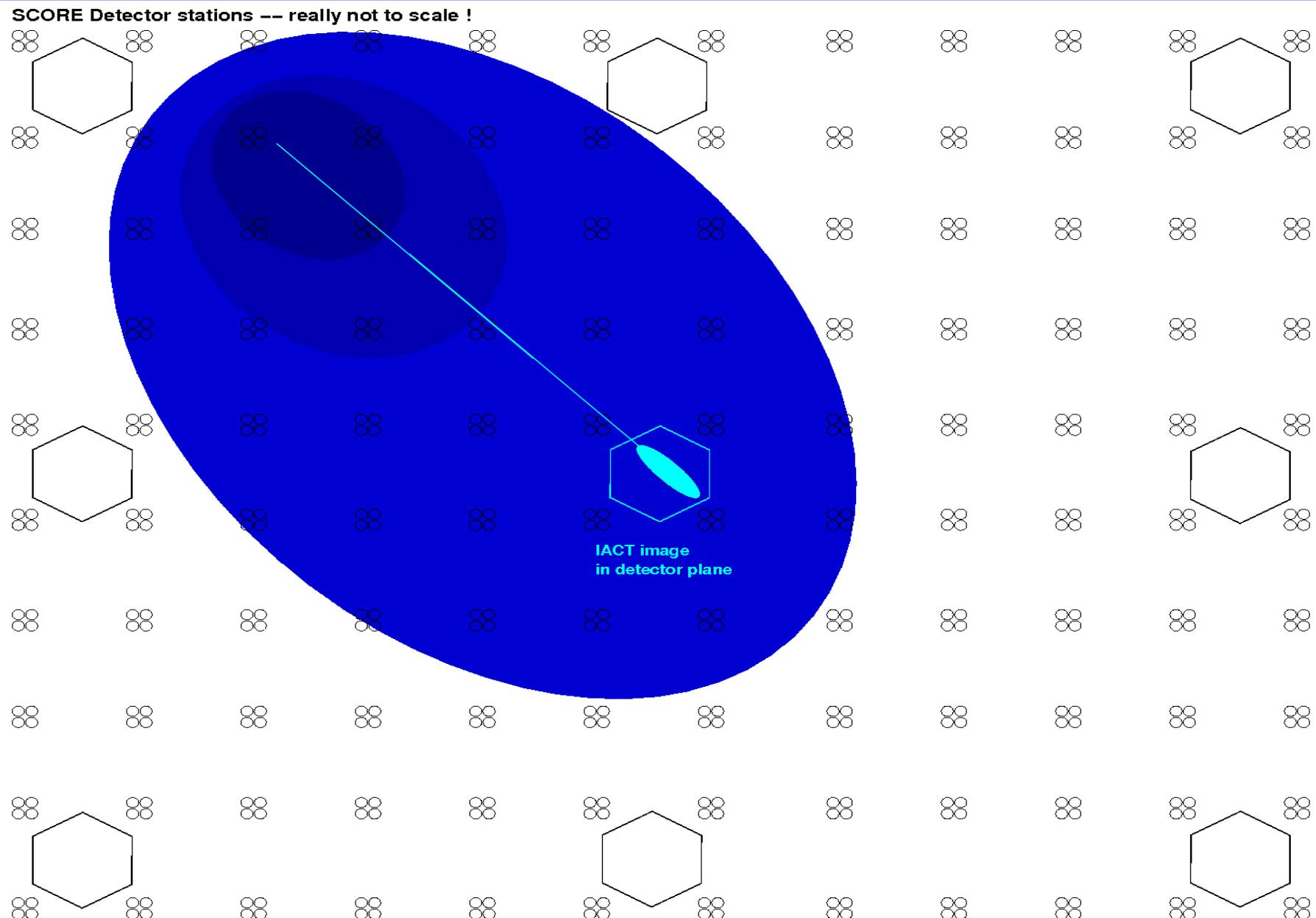
HiSCORE prototype at TUNKA



Alternatives / Extensions

- 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
 - **Daytime-measurements** with scintillator material in lid:
100% duty cycle
 - **Muon detector:** much better g/h separation
- Combination with imaging technique:
 - provide core-reconstruction for low-density telescope grid
(even monoscopic ?)
 - Instrumentation of larger area for highest energies
- Combination / cross-calibration with radio detection technique ?

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 – might be overcome by using timing stereo at large zenith angles.
- Working on ... testing this in simulation

Plans

HiSCORE 1st prototype at TUNKA 2011

HiSCORE prototype at AUGER ~2012

PhD position from Helmholtz alliance, HAP

Engineering array at TUNKA:
start deployment ~2012

Site search: south, clear, dark, (low?), flat

HiSCORE: 10—100 km² in 2015 ?

Summary

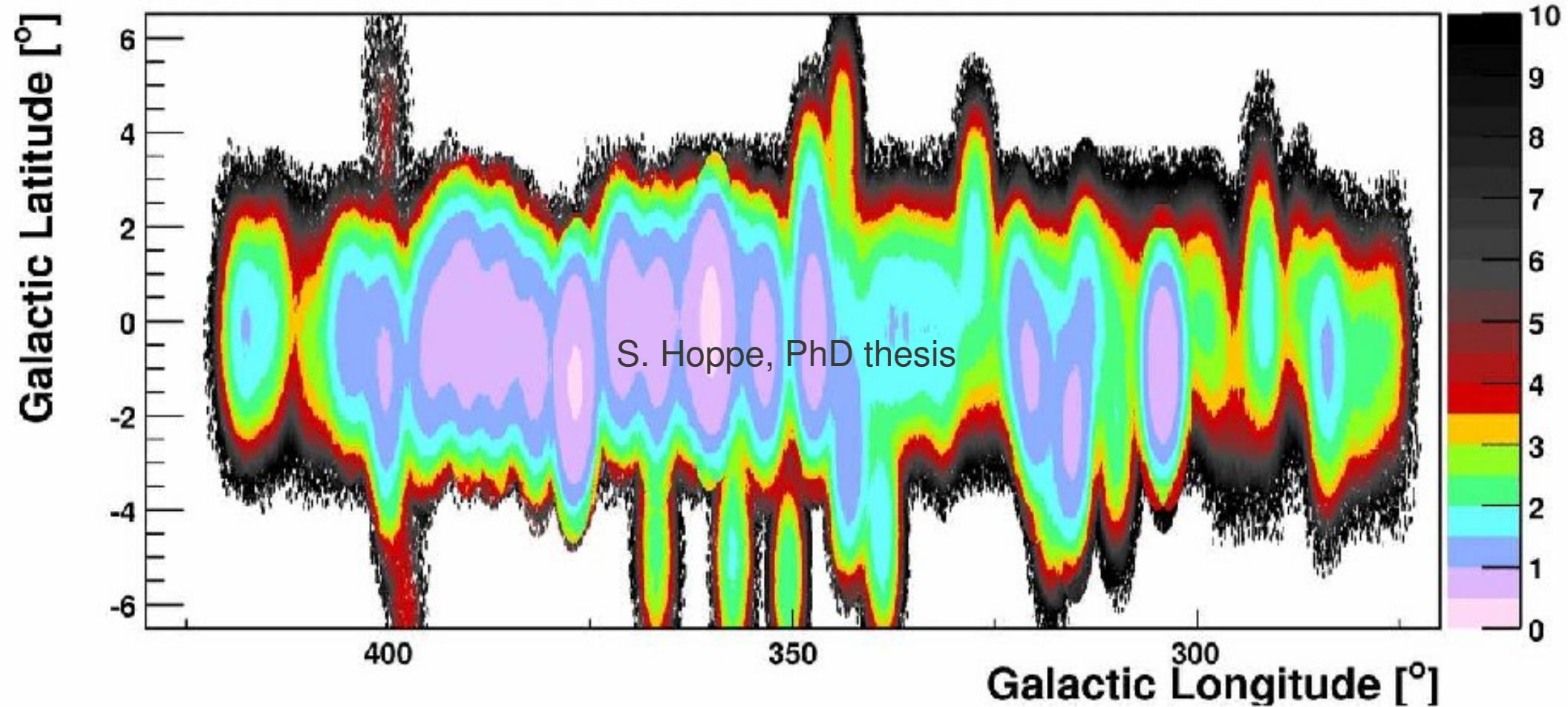
- **Many physics cases beyond 10 TeV primary energy**
The sensitivity goal is already reached by 10km² stage
- **Detector fully simulated**
- **R&D advanced**
80% of components developed
- **Cooperation with TUNKA started**
- **Further ideas:**
Combination with radio / scintil. / imaging technique under stud

References

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- [2] H. Fesefeldt, Report **PITHA-85/02** (1985), RWTH Aachen
- [3] K. Bernlöhr (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)**, Proc. of the ICRC 2009, arXiv e-print (arXiv:0909.0445v1)
- [6] **D. Hampf, M. Tluczykont & D. Horns (2009)**, 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 TeV)

$$dN/dE = 4.26 \cdot 10^{-12} (E/\text{TeV})^{-2} e^{-\sqrt{x/300 \text{ TeV}}} [\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}]$$

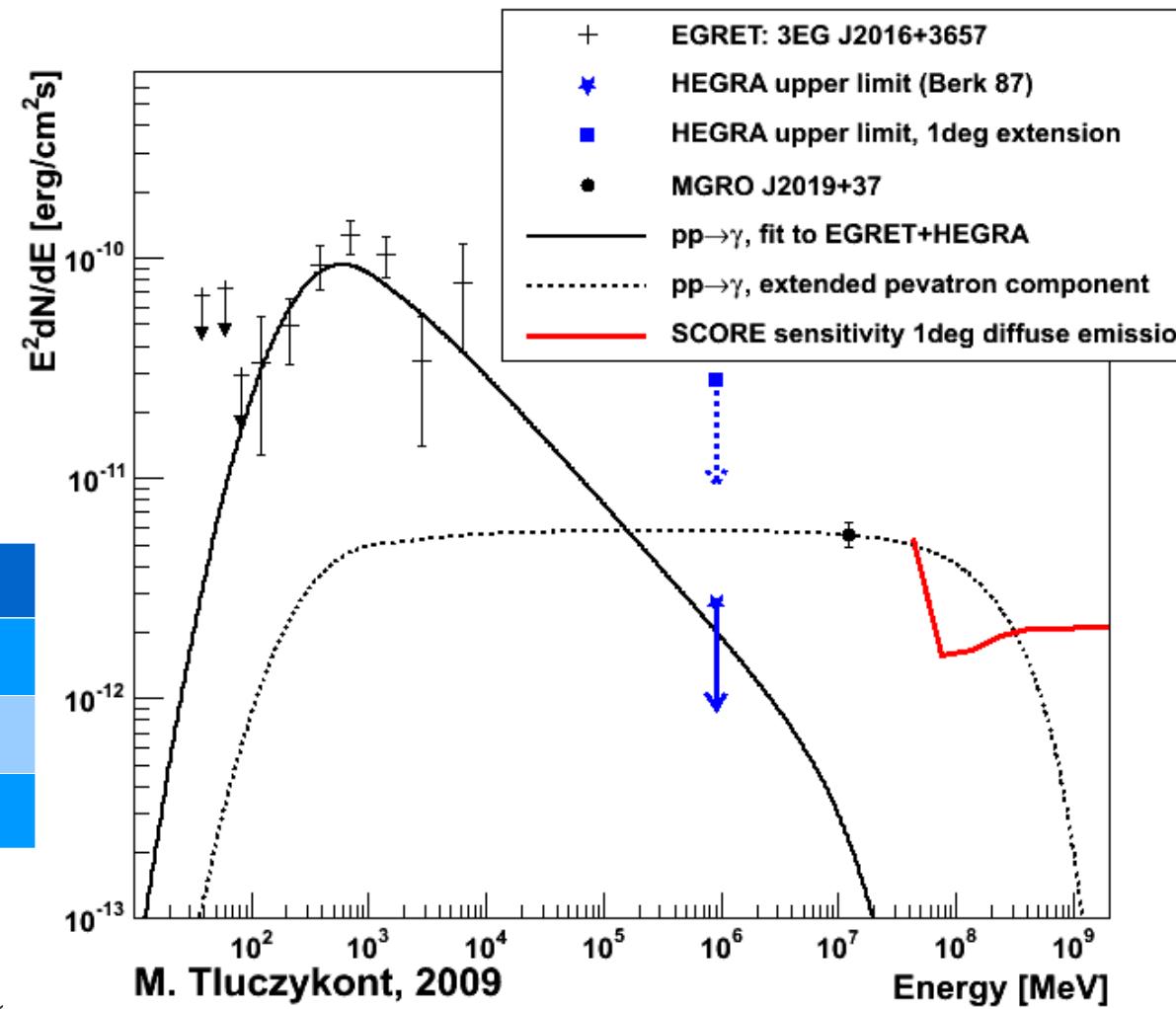
Fold dN/dE and Hörandel
w/ post-reconstruction area

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



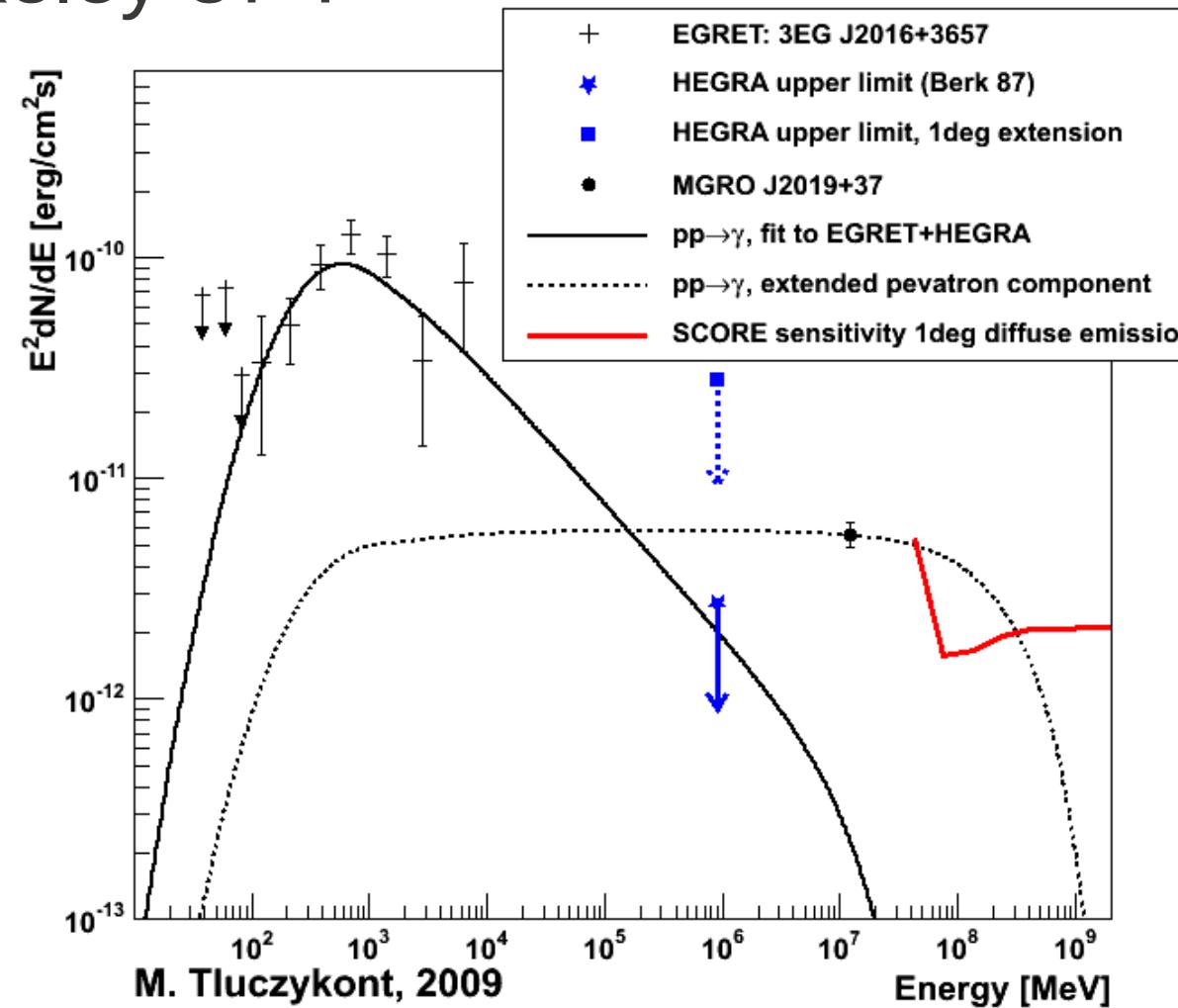
Pevatron emission from Cygnus ?

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

p-p cross-section

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

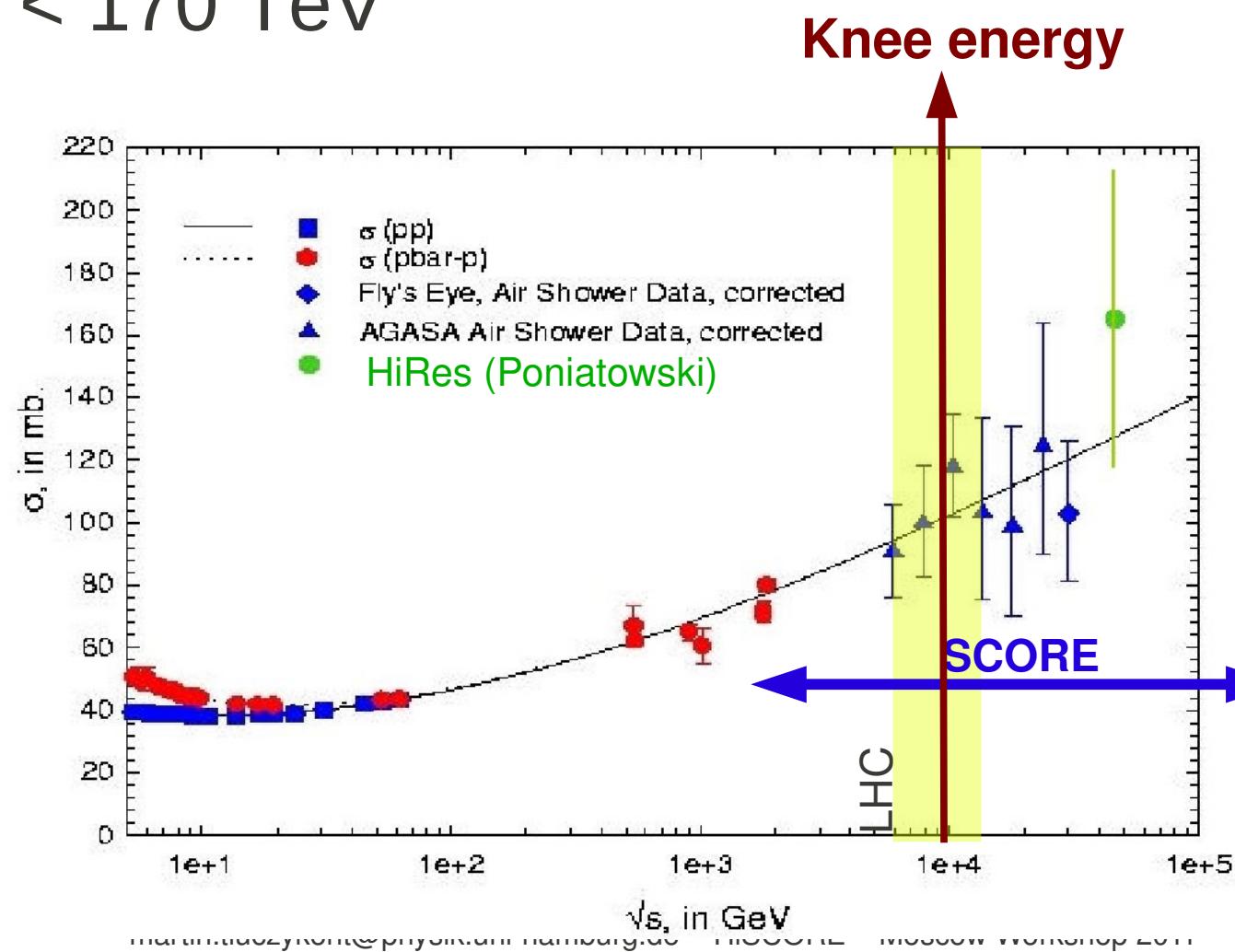
SCORE: $1.7 < E_{CM} < 170 \text{ TeV}$

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

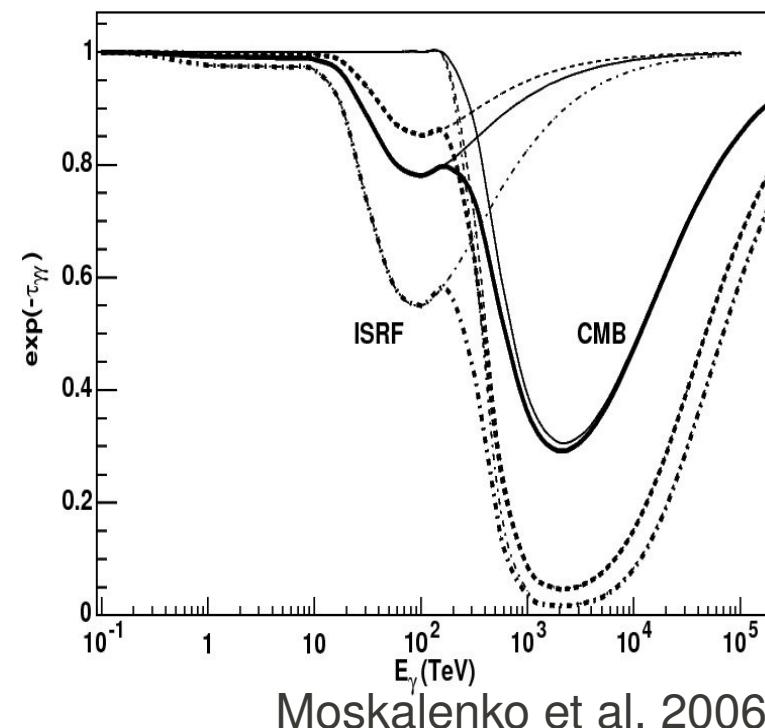
CMB well known: **distance estimate?**

Weakening of absorption by:

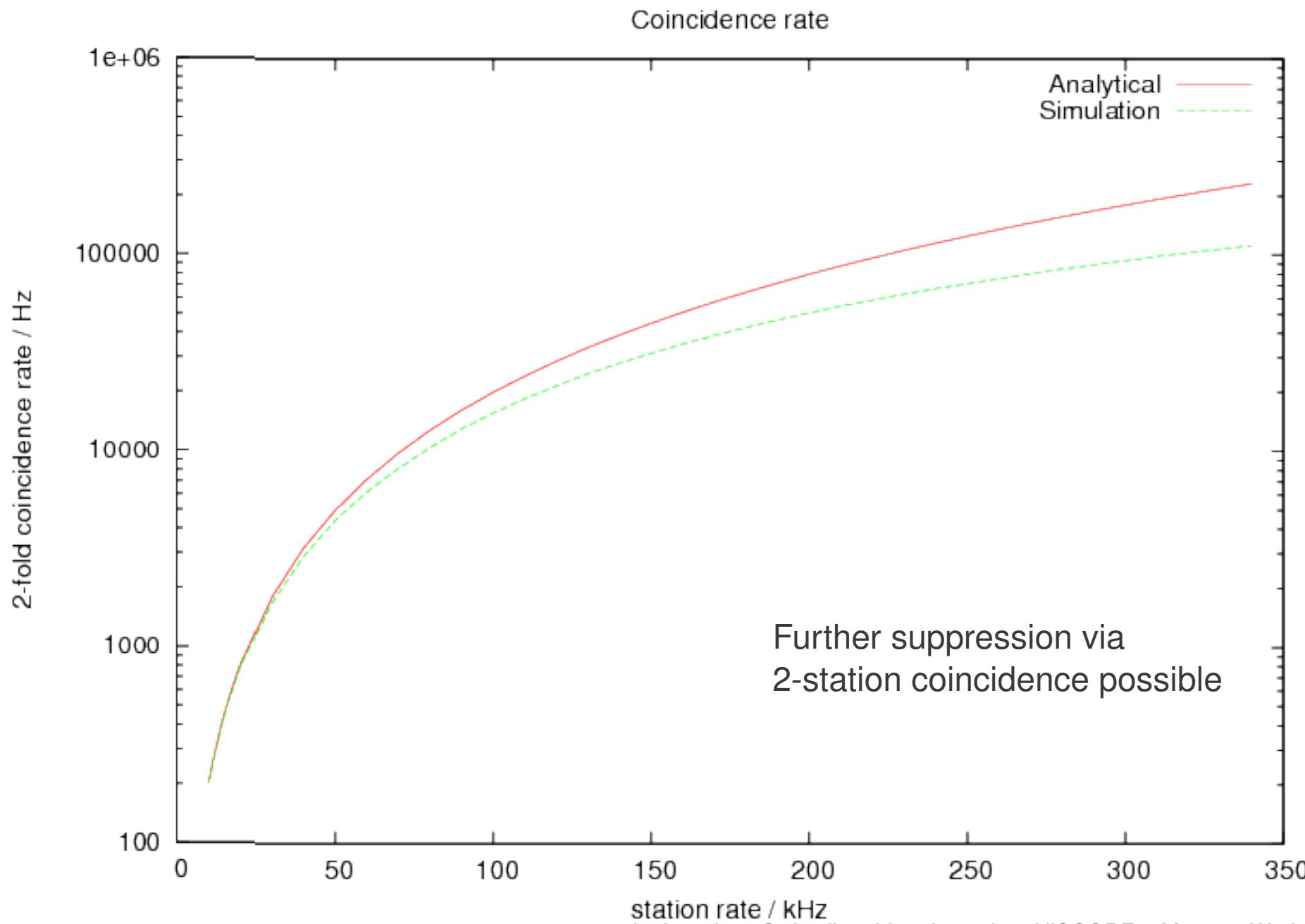
Photon / axion conversion in Galactic Magnetic field

Photon / hidden photon oscillation

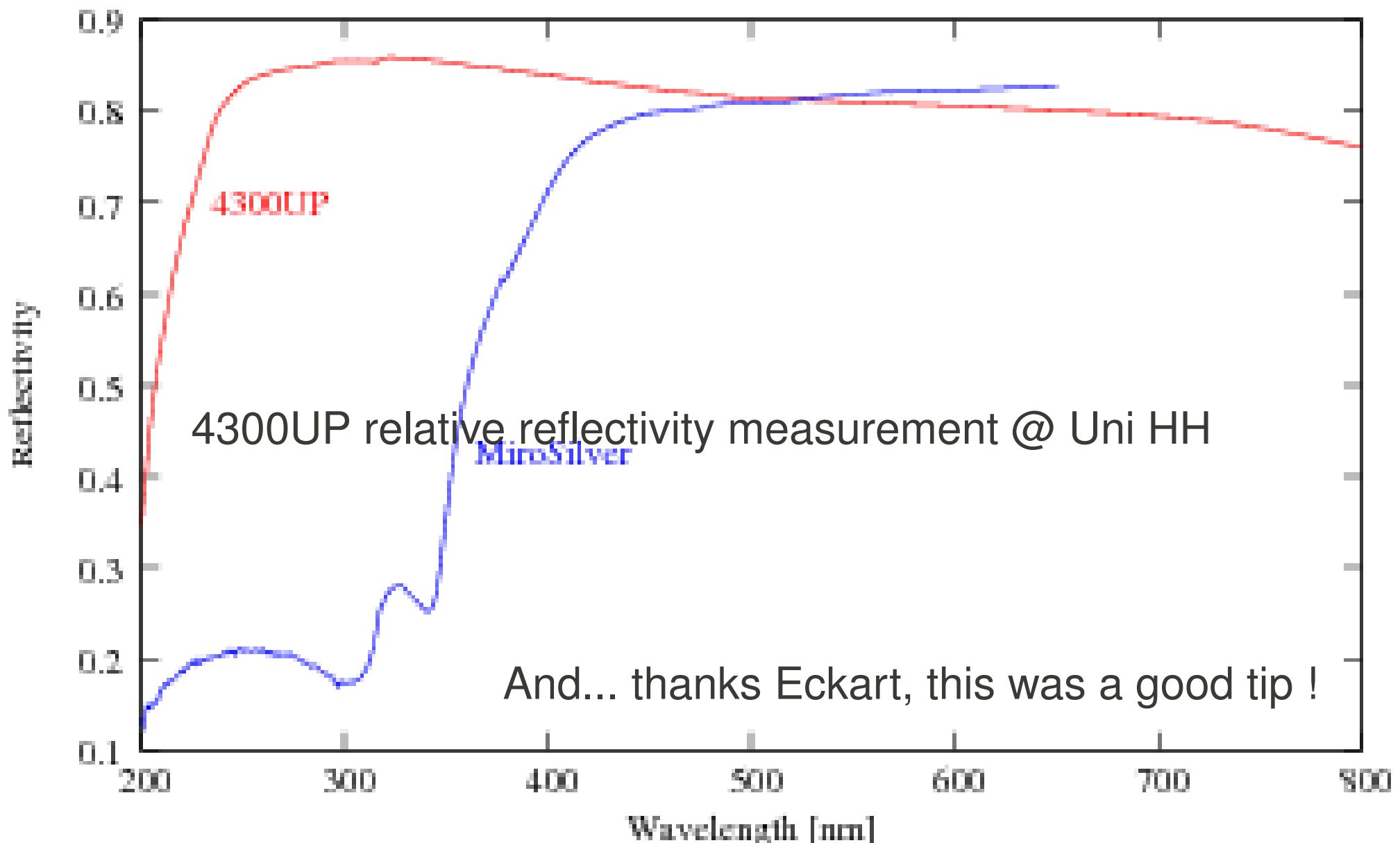
Lorentz invariance violation (modification of e^+e^- threshold)



Expected night-sky background trigger rate



Hardware Prototyping / Testing



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

