Astroparticle and particle physics with HiSCORE

Martin Tluczykont for the HiSCORE group
D. Horns, D. Hampf, R. Nachtigall, U. Einhaus, M. Kunnas, T. Kneiske
Institut für Experimentalphysik, University of Hamburg

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Physics motivations

Principle of the array

Status & outlook

Universität Hamburg

Acronyms

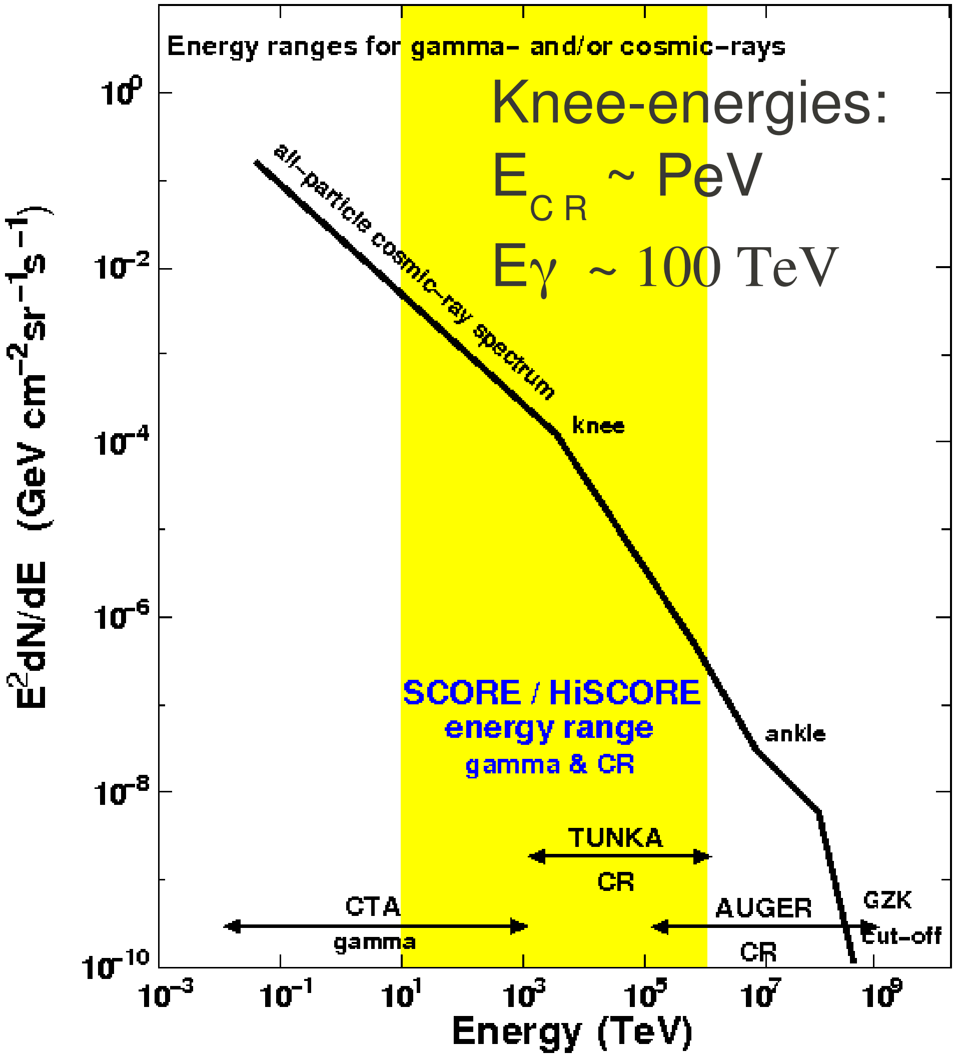
SCORE

Study for a Cosmic ORigin Explorer ~ 10 km²

HiSCORE

Hundred*i Square-km Cosmic ORigin Explorer ~ 100+ km²

HiSCORE aims



Cosmic-rays:
100 TeV < E_{CR} < 1 EeV

Gamma-rays:
$E\gamma$ > 10 TeV

Large area: 10-100 km²

Large Field of view: ~ 0.6 sr

ASPERA recognizes the importance of

"development of ground-based wide-angle gamma-ray detectors"

ASPERA

We propose HiSCORE !

Astroparticle Physics @ E > 10 TeV

Gamma-ray Astronomy

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

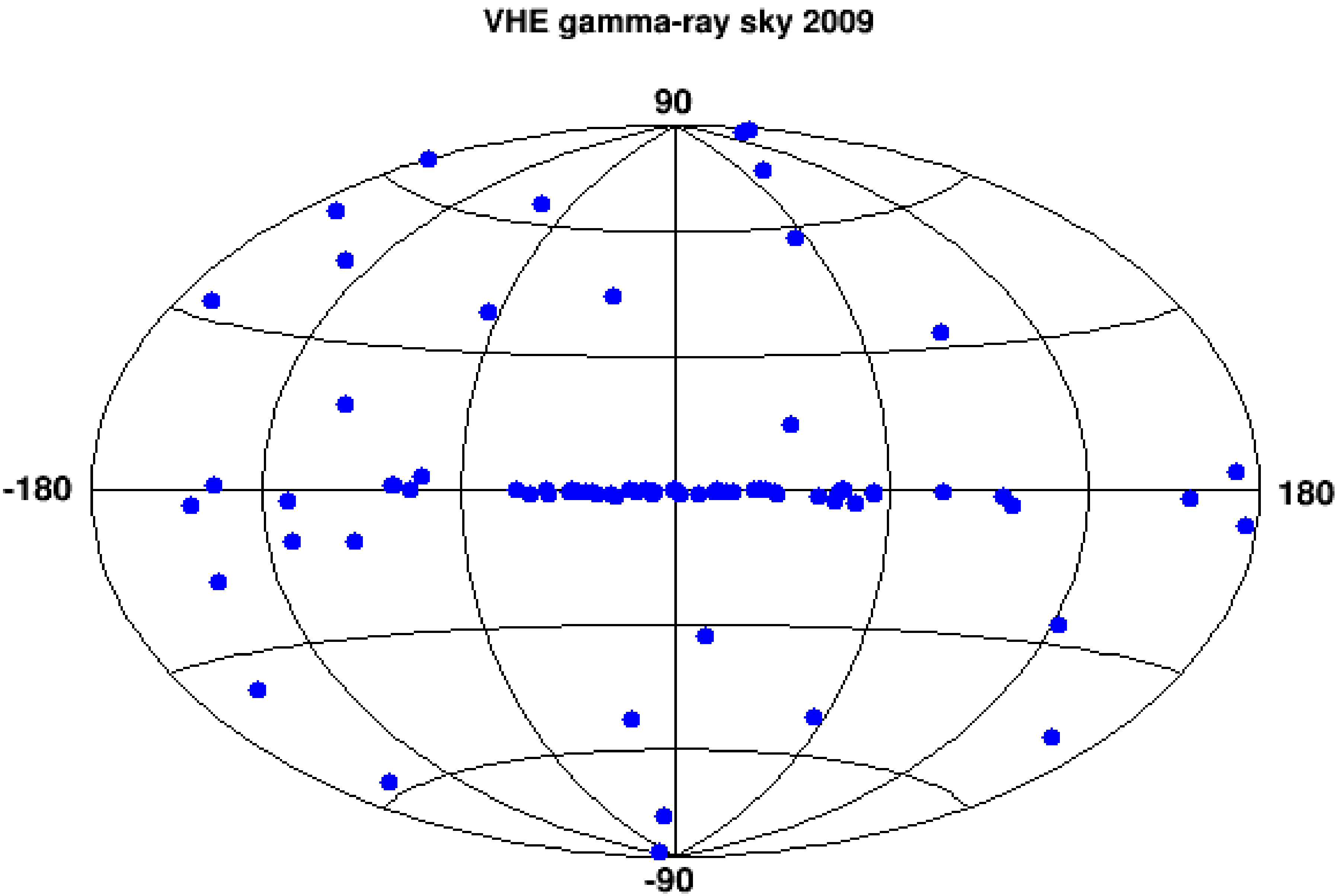
Particle physics beyond LHC

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

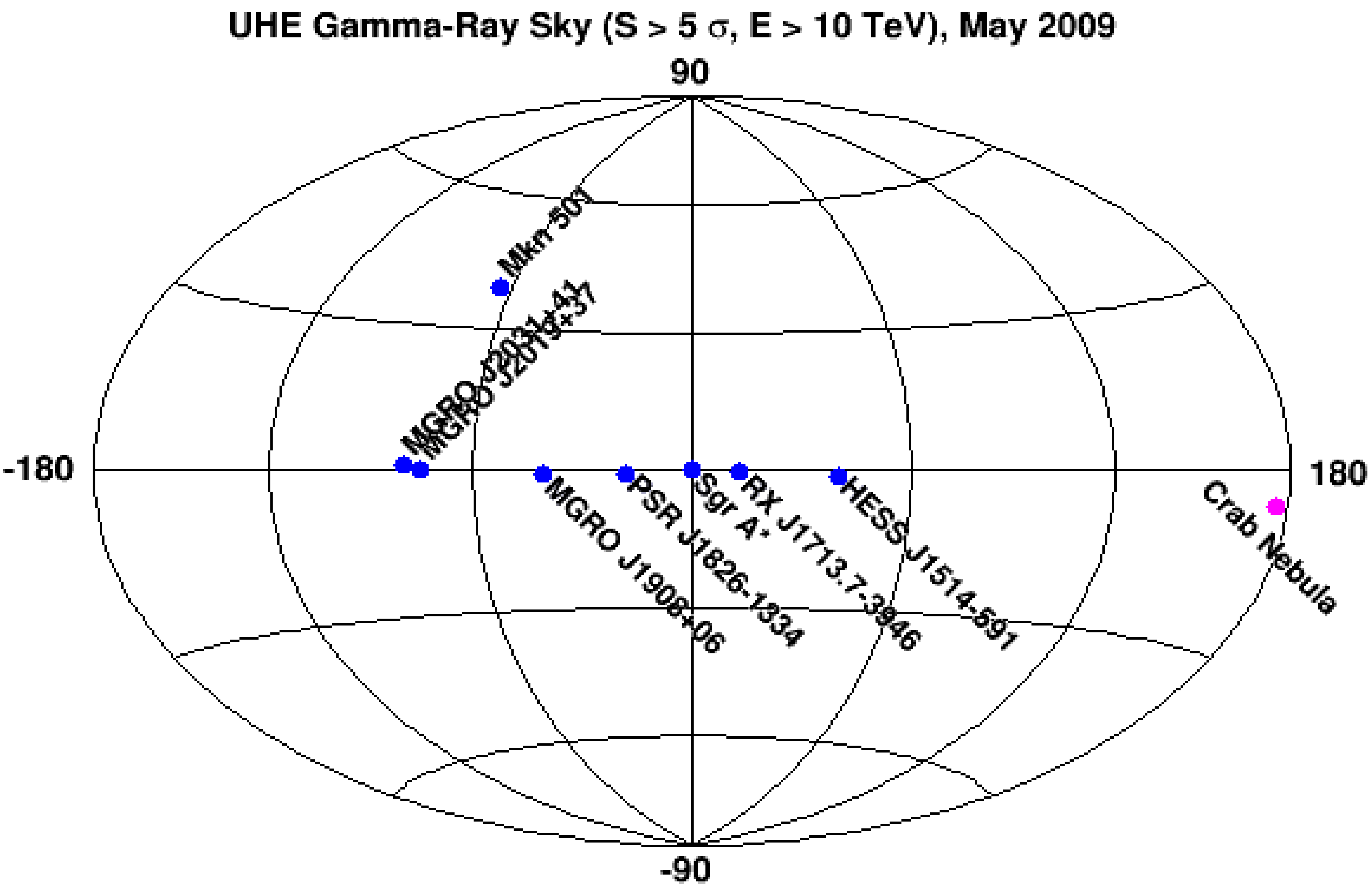
Charged cosmic ray physics

Composition / anisotropies
Sub-knee to pre-ankle

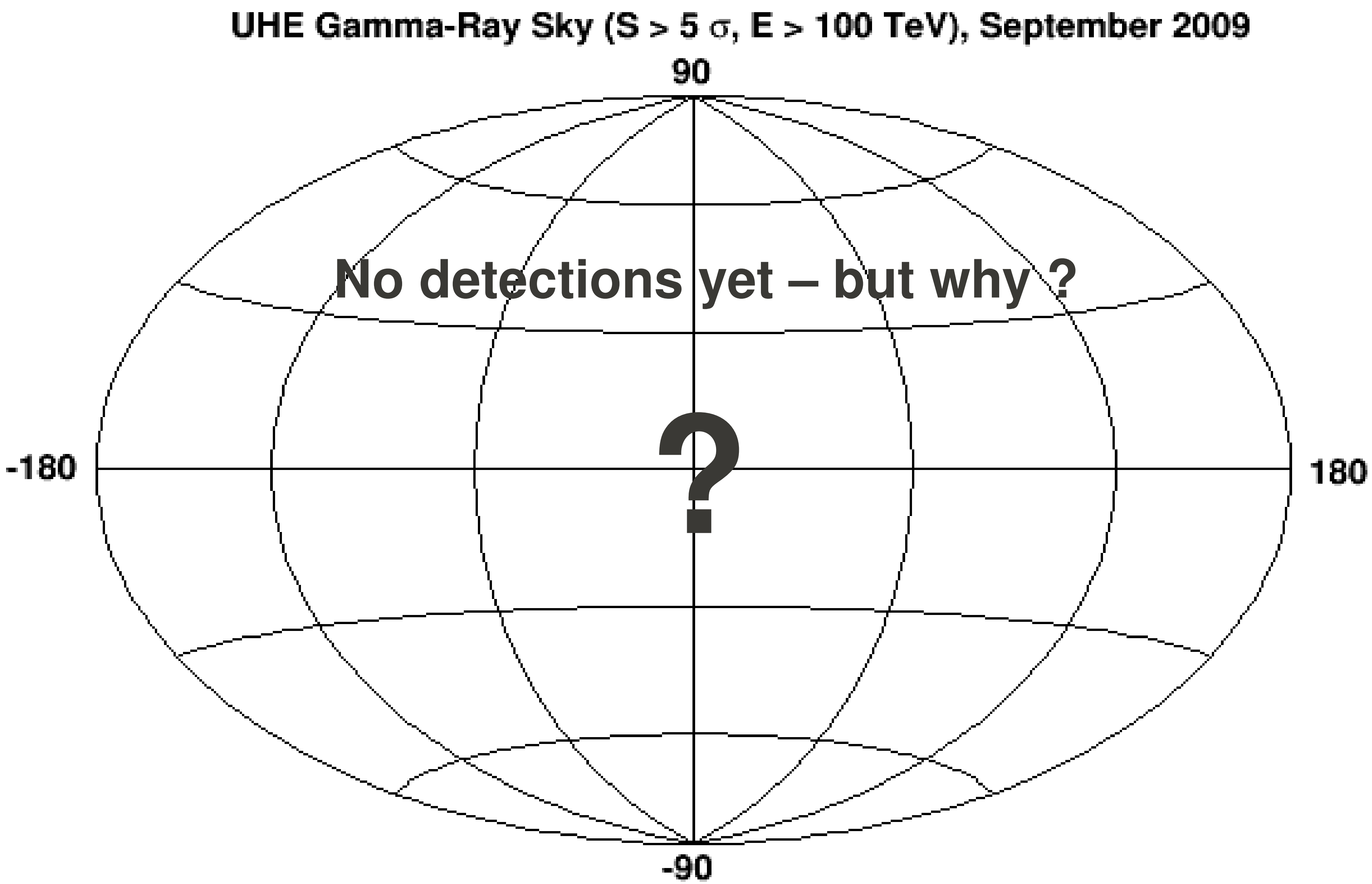
Gamma-Ray Sky, E>100GeV



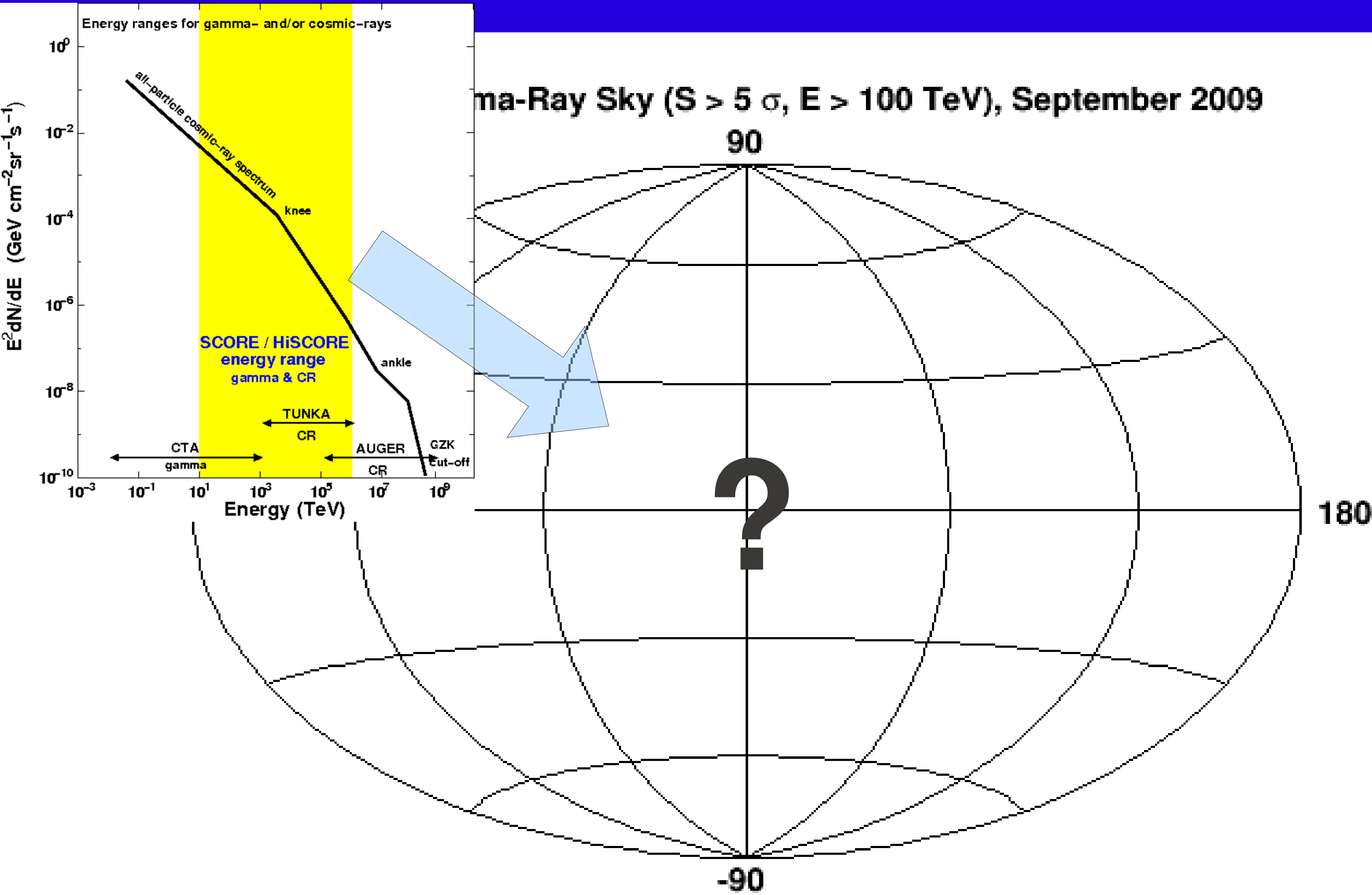
Gamma-Ray Sky, E>10TeV



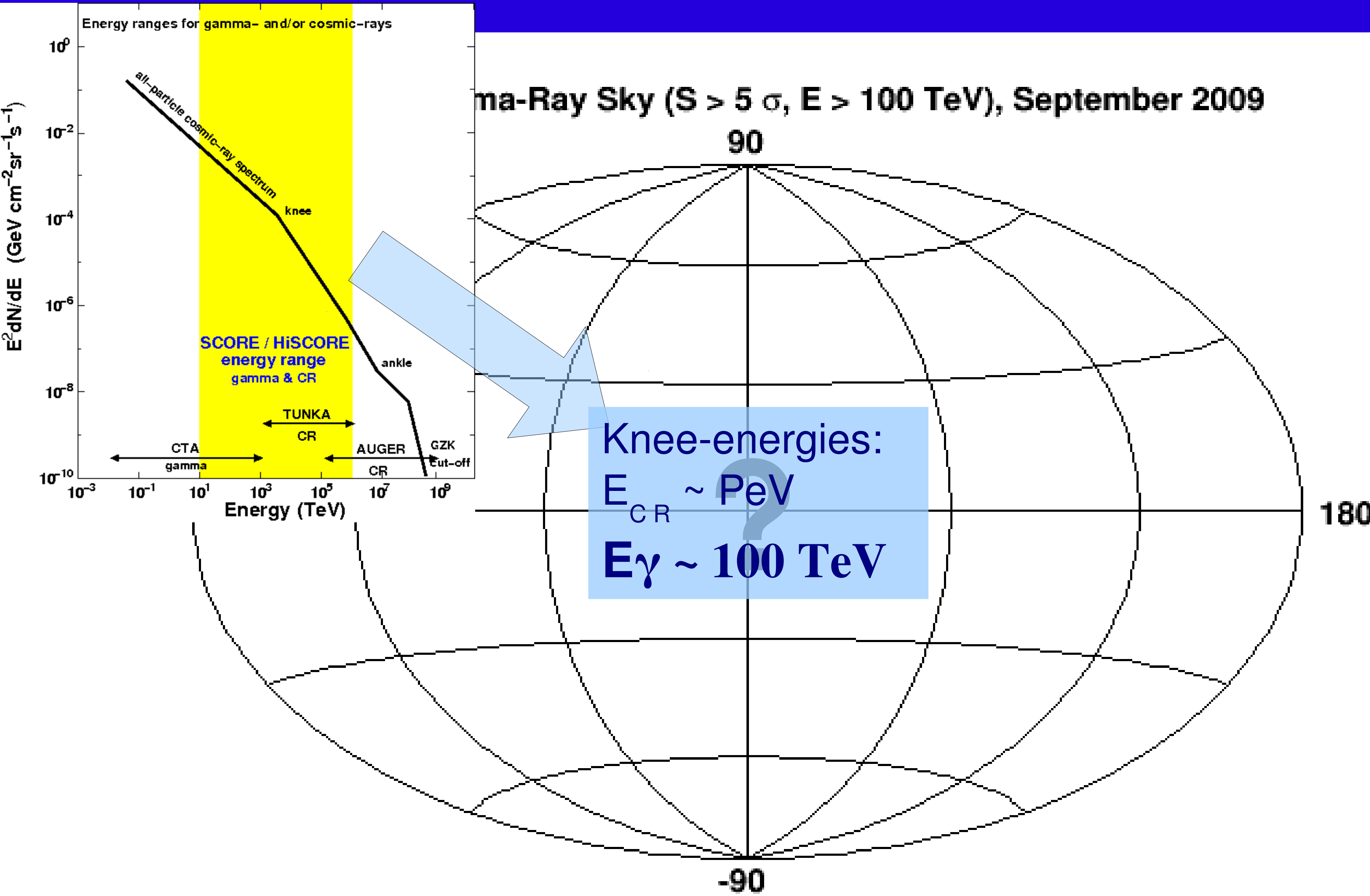
Gamma-Ray Sky, E>100TeV



Gamma-Ray Sky, E>100TeV



Gamma-Ray Sky, E>100TeV

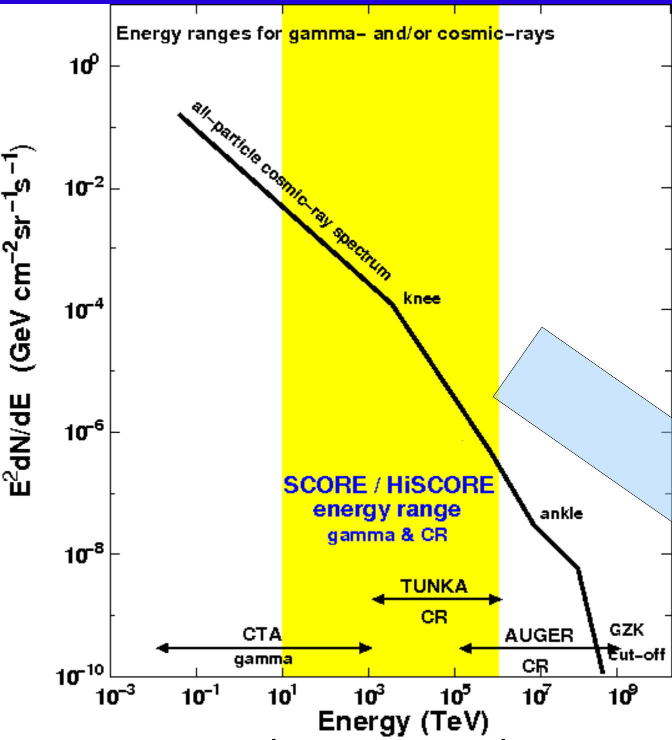


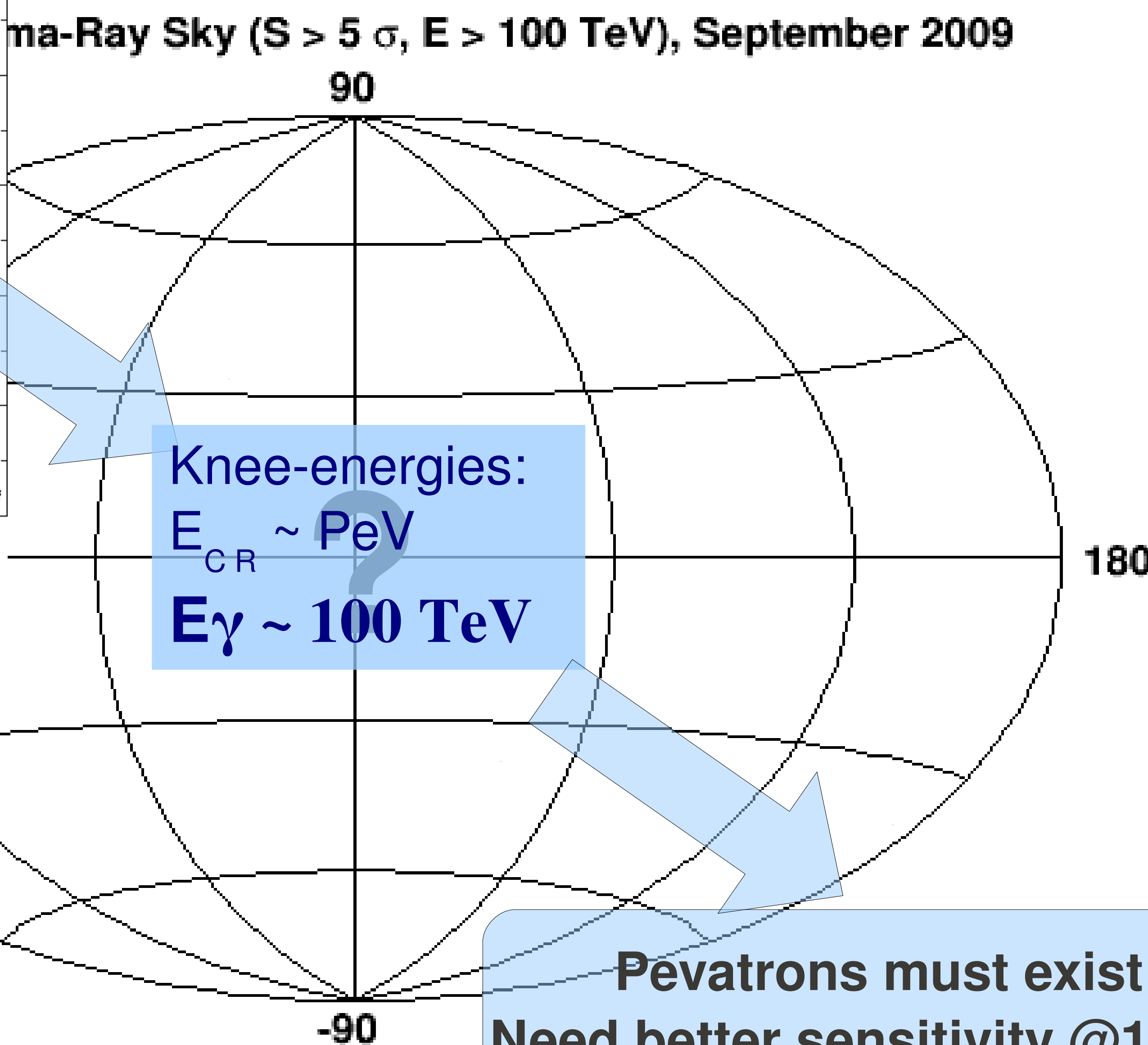
Knee-energies:

E_{CR} ~ PeV

Eγ ~ 100 TeV

Gamma-Ray Sky, E>100TeV





Knee-energies:

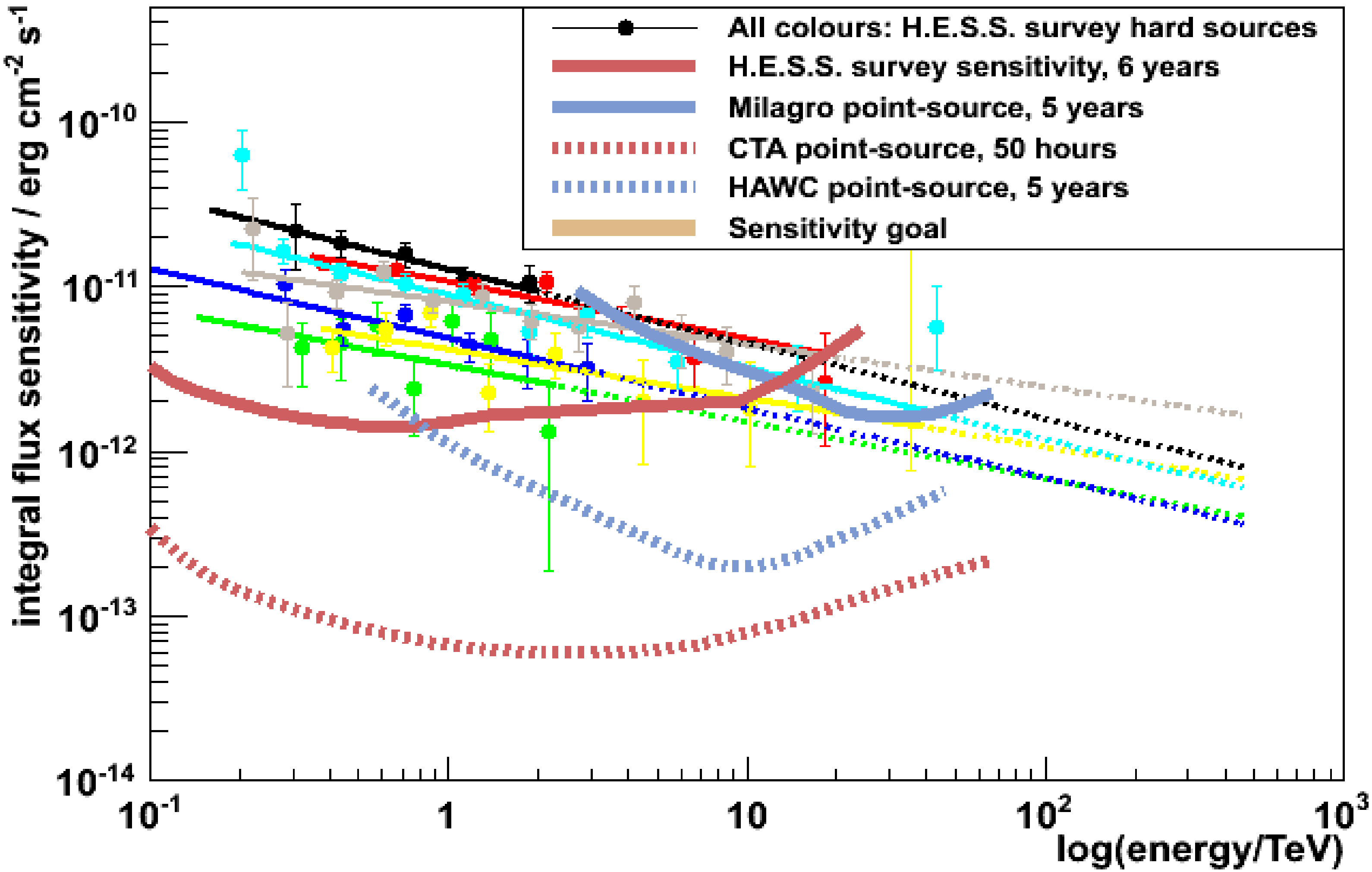
E_{CR} ~ PeV

Eγ ~ 100 TeV

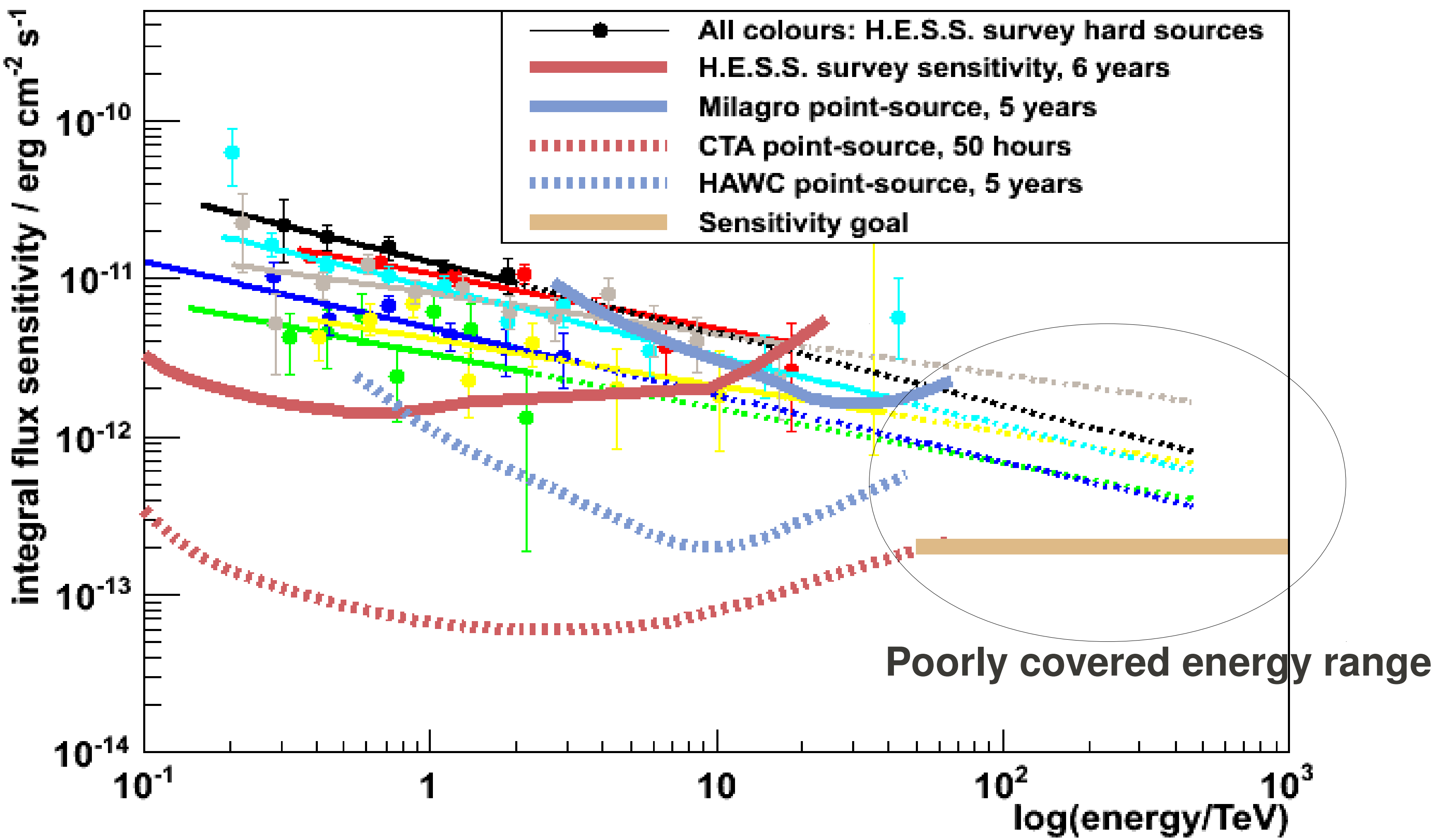
Pevatrons must exist !

Need better sensitivity @100TeV

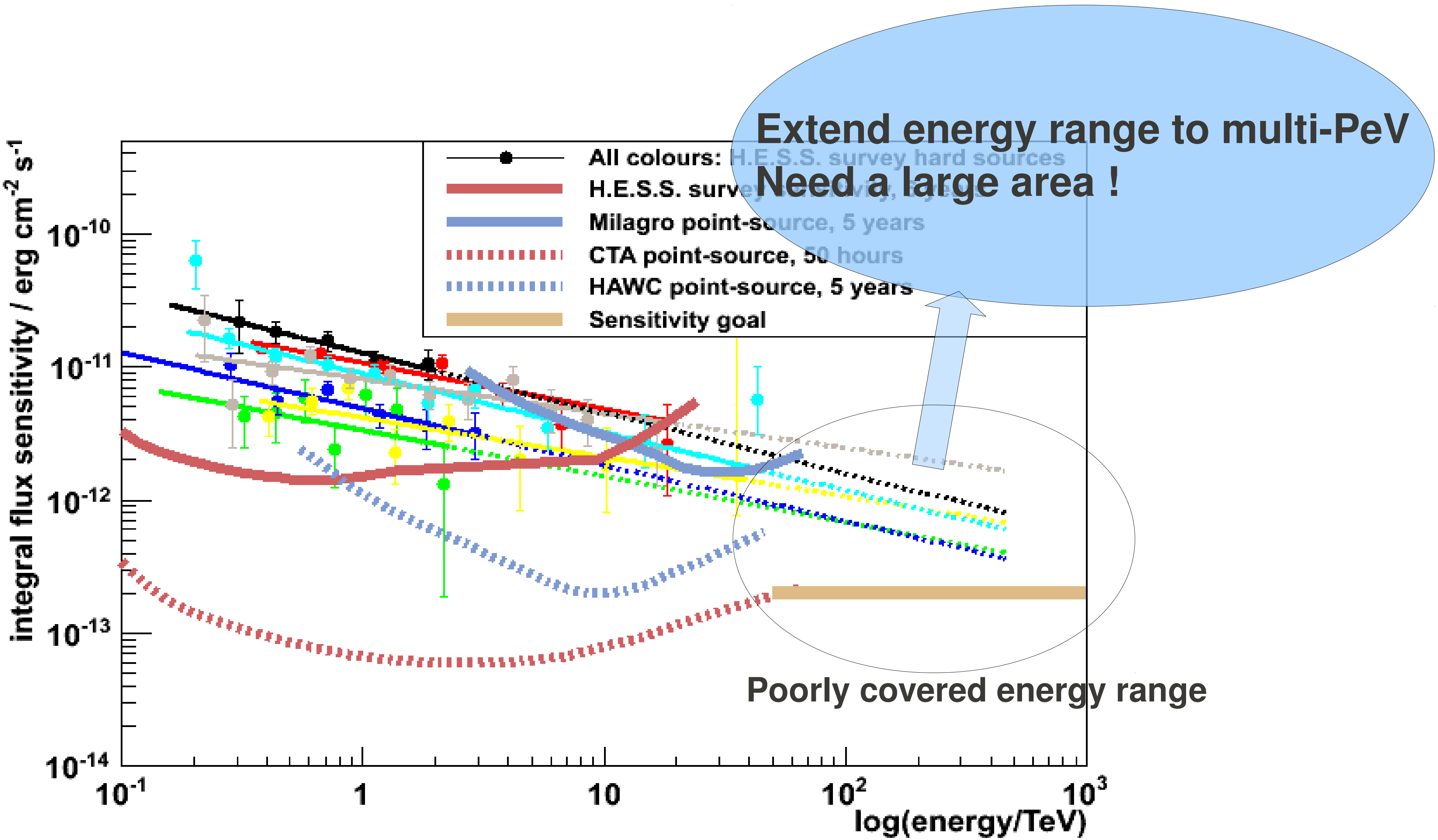
UHE Gamma-rays



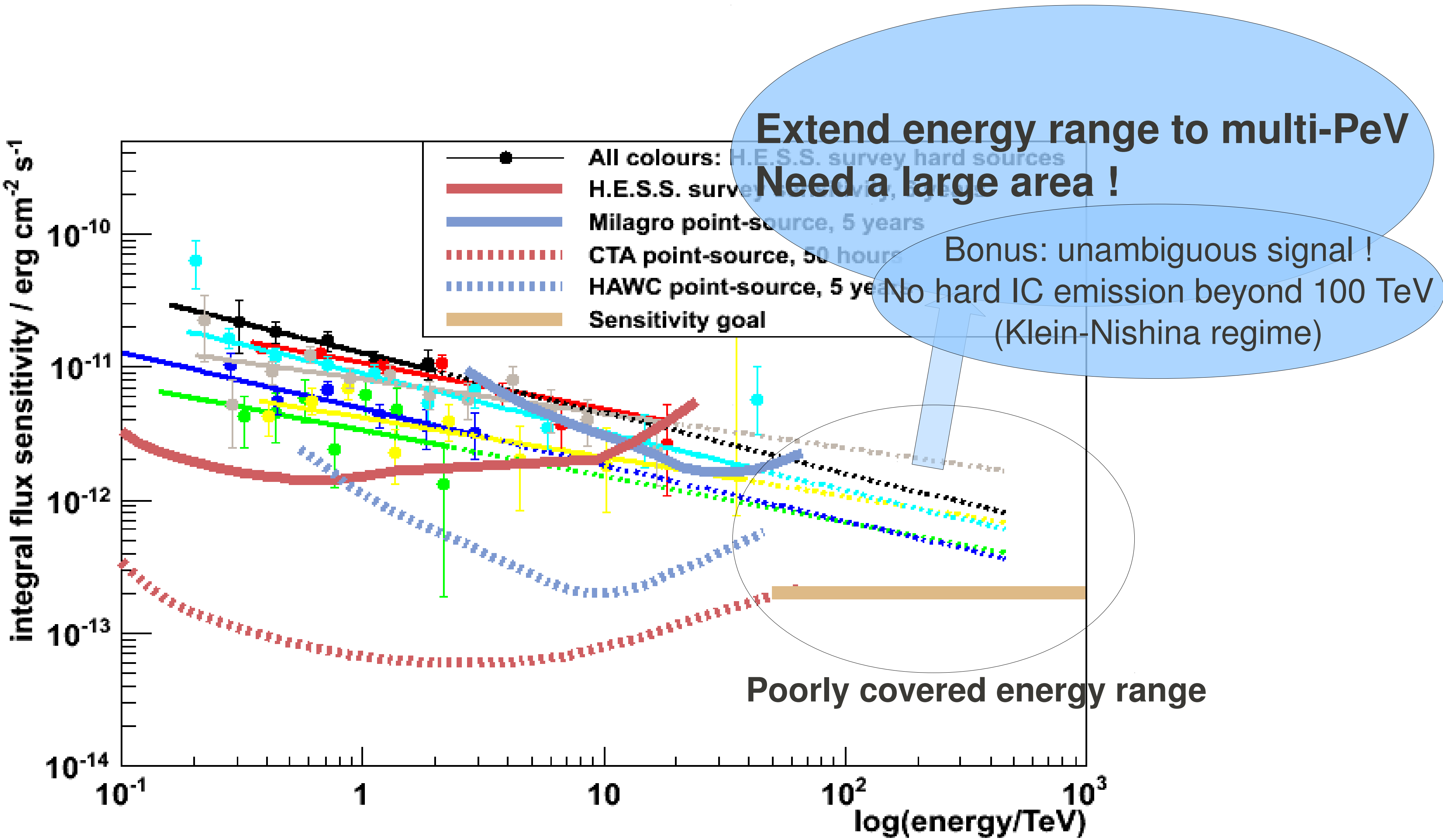
UHE Gamma-rays



UHE Gamma-rays



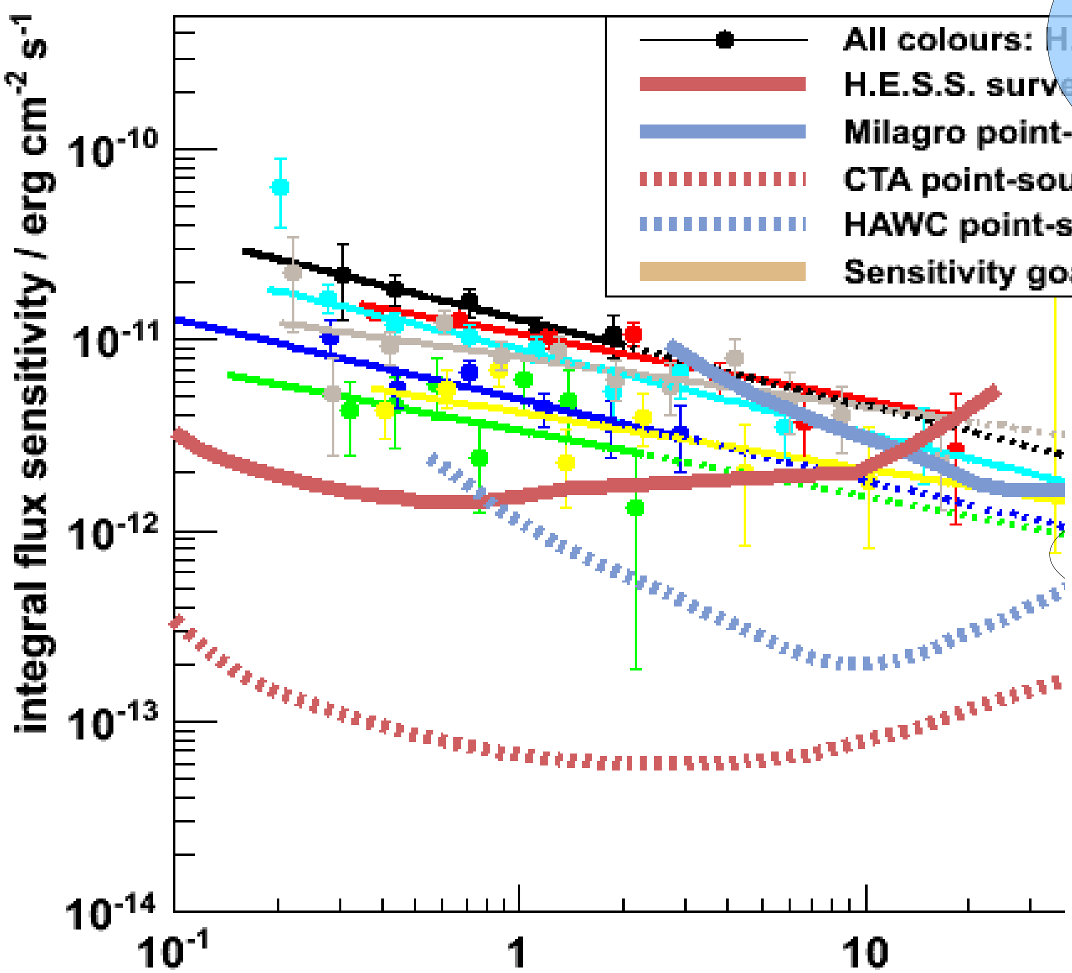
UHE Gamma-rays



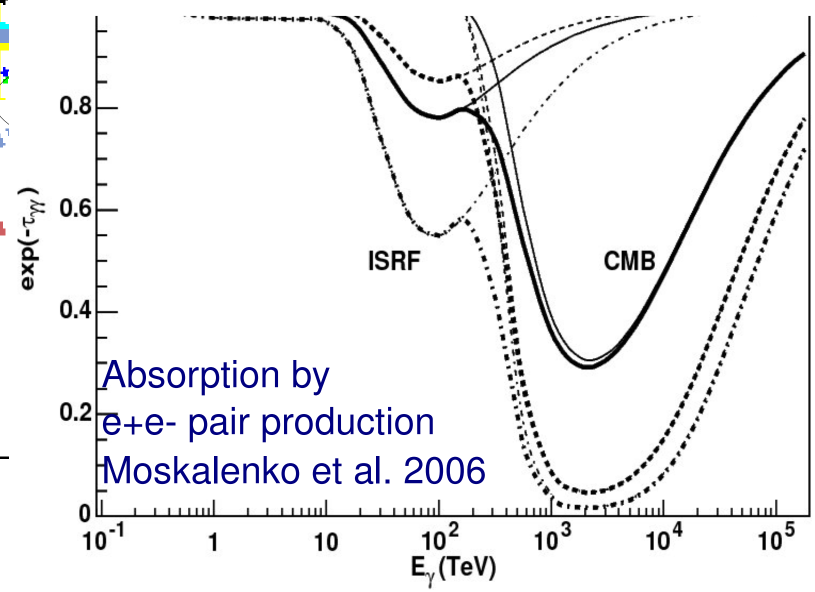
UHE Gamma-rays

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

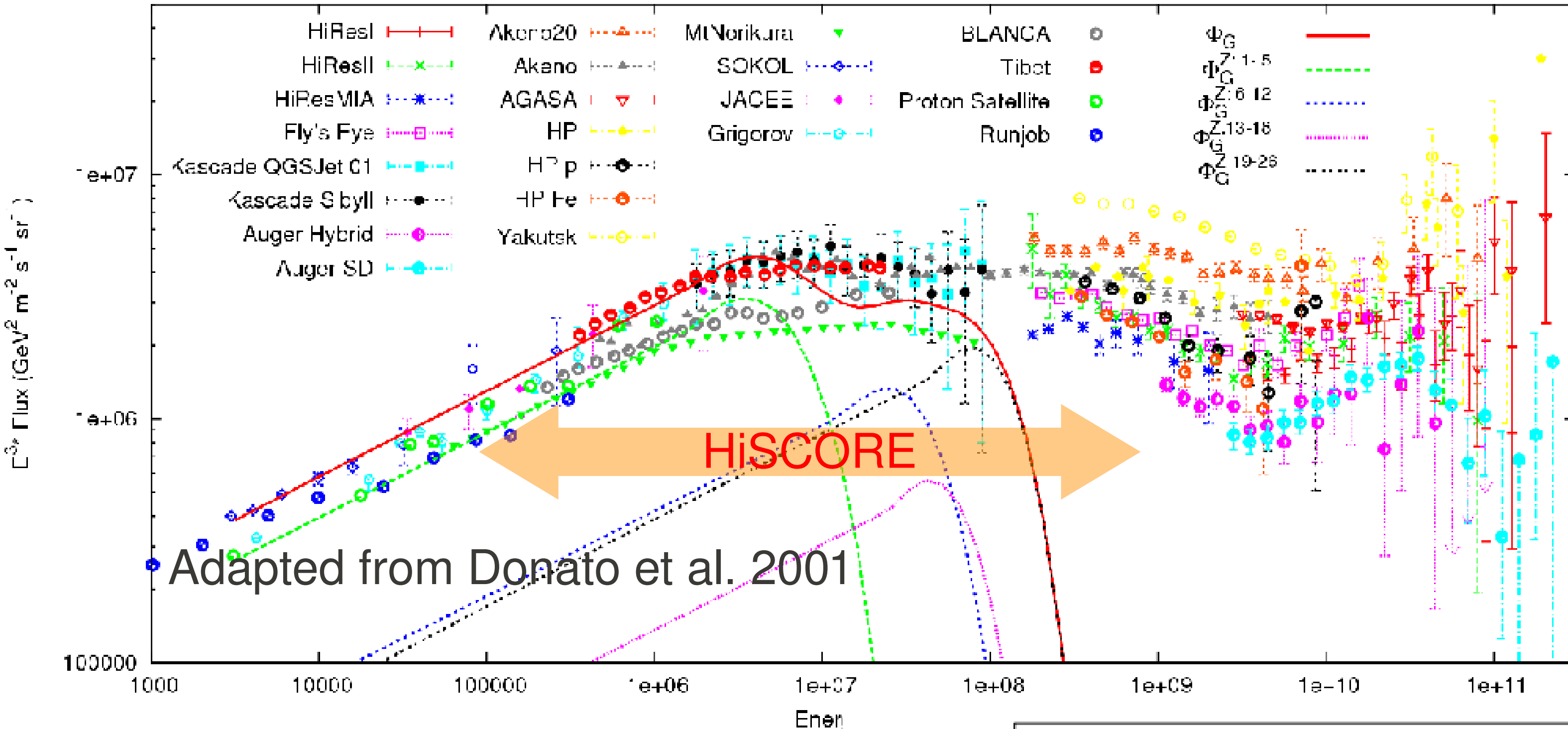
Bonus: unambiguous signal !
No hard IC emission beyond 100 TeV
(Klein-Nishina regime)

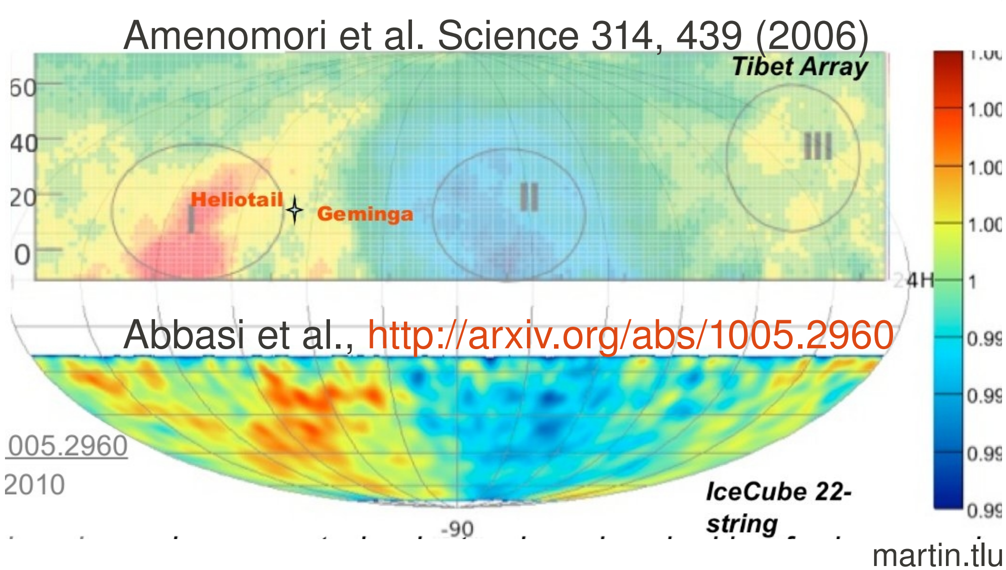


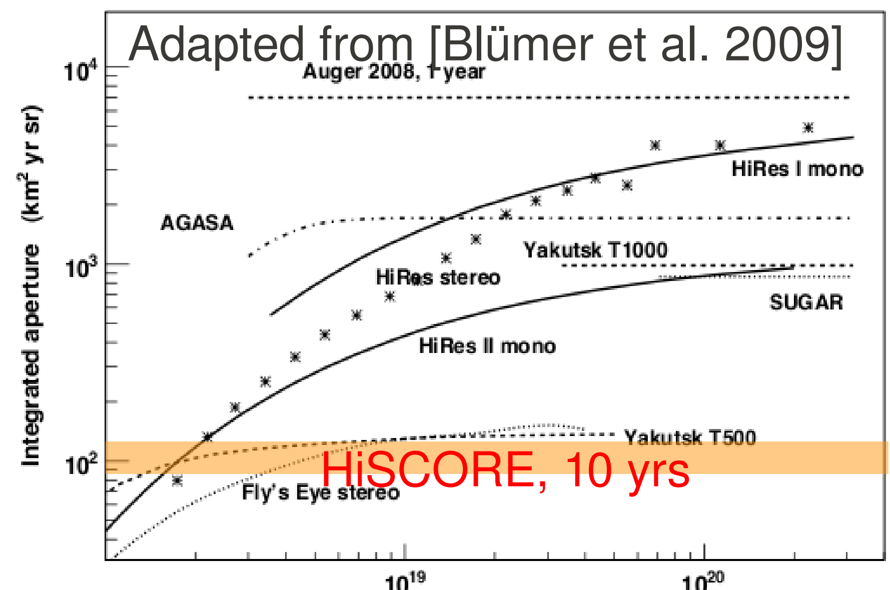
E~100TeV: absorption in ISRF relevant
E~1PeV: strong CMB absorption
→ use cutoff feature for distance measurement ?



Cosmic rays

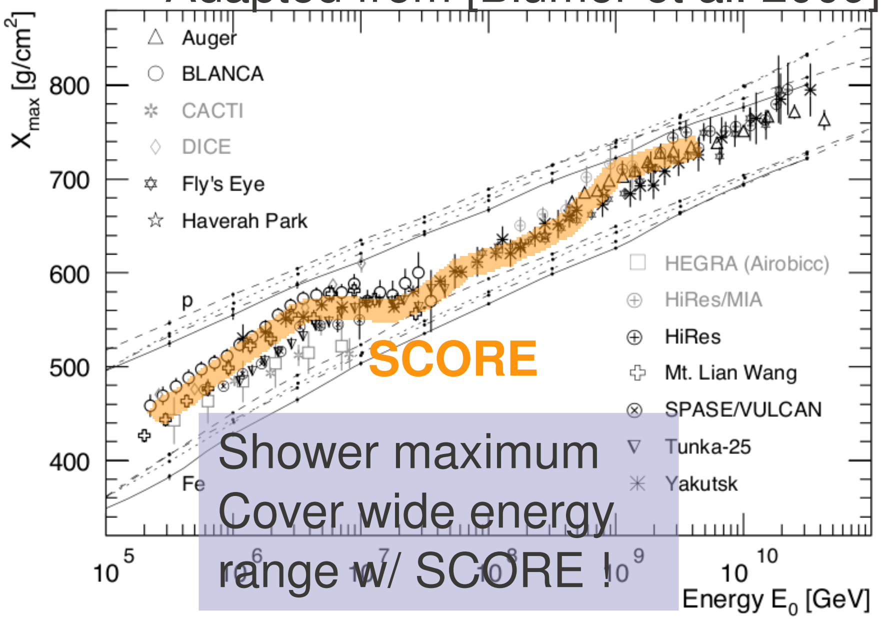

HiResI
HiResII
HiResMIA
Fly's Eye
Kascade QGSJet 01
Kascade Sibyll
Auger Hybrid
Auger SD
Akeno20
Akeno
AGASA
HP
HP p
HP Fe
Yakutsk
MtNorikura
SOKOL
JACEE
Grigorov
BLANCA
Tibet
Proton Satellite
Runjob
HiSCORE
Adapted from Donato et al. 2001
100000
1000
10000
100000
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11


Amenomori et al. Science 314, 439 (2006)
Tibet Array
Heliotail
Geminga
I
II
III
60
40
20
0
Abbasi et al., http://arxiv.org/abs/1005.2960
IceCube 22-string
-90
005.2960
2010
martin.tlu

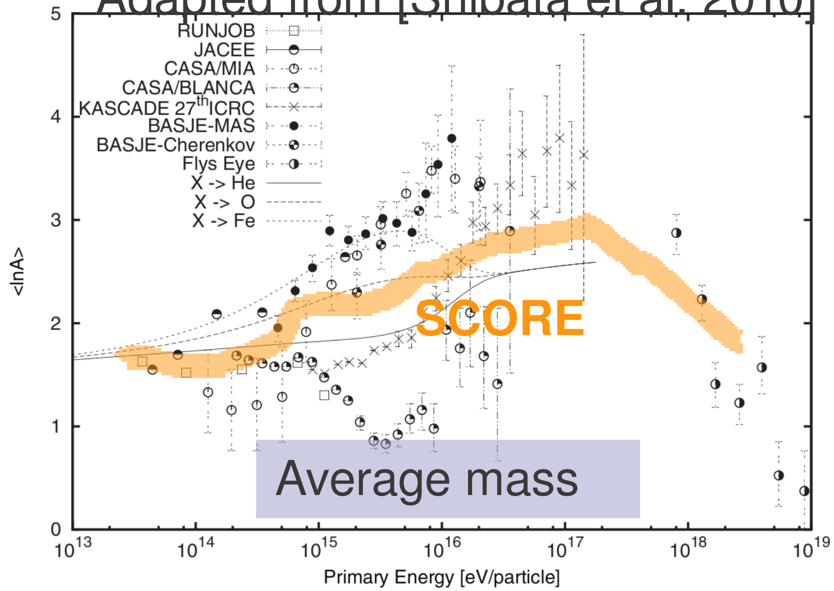

Adapted from [Blümer et al. 2009]
Auger 2008, 1 year
Integrated aperture (km² yr sr)
AGASA
HiRes I mono
Yakutsk T1000
HiRes stereo
SUGAR
HiRes II mono
Yakutsk T500
HiSCORE, 10 yrs
Fly's Eye stereo
10^4
10^3
10^2
10^19
10^20

Cosmic rays

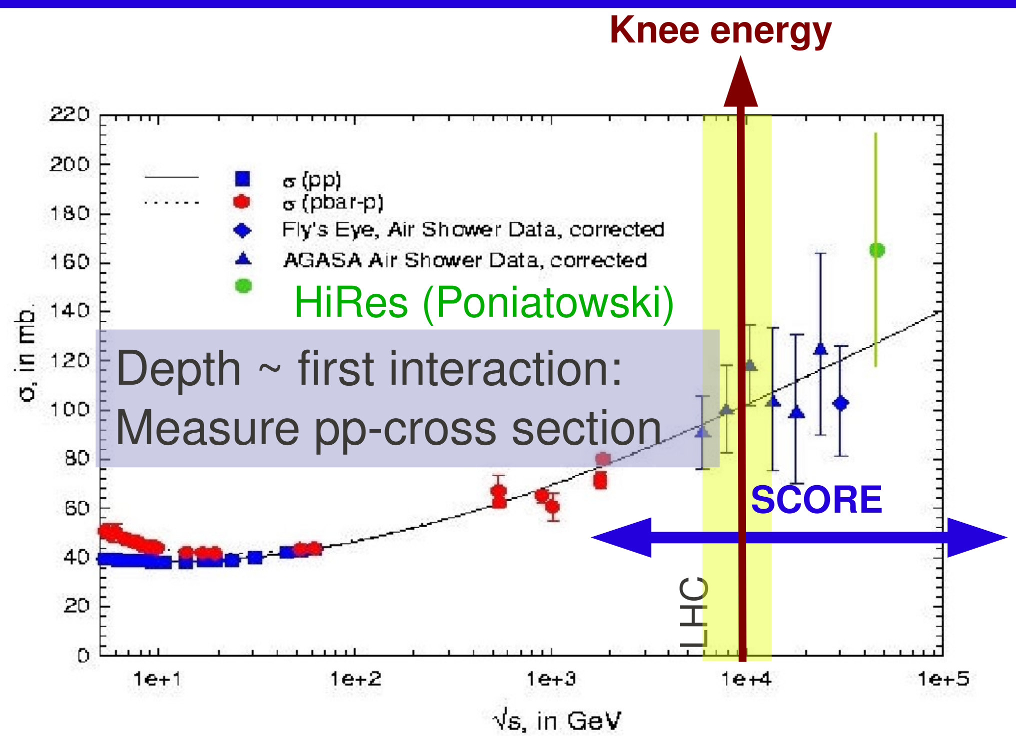
Adapted from [Blümer et al. 2009]



Adapted from [Shibata et al. 2010]



Particle physics



Further particle physics topics:

- Axion search: photon/axion conversion & reconversion → absorption-free propagation
- Hidden sector
- Heavy dark matter

The detector

Goals:

Energy range goal: 10 TeV – 1 EeV

Area goal: 10 – 100+ km^2

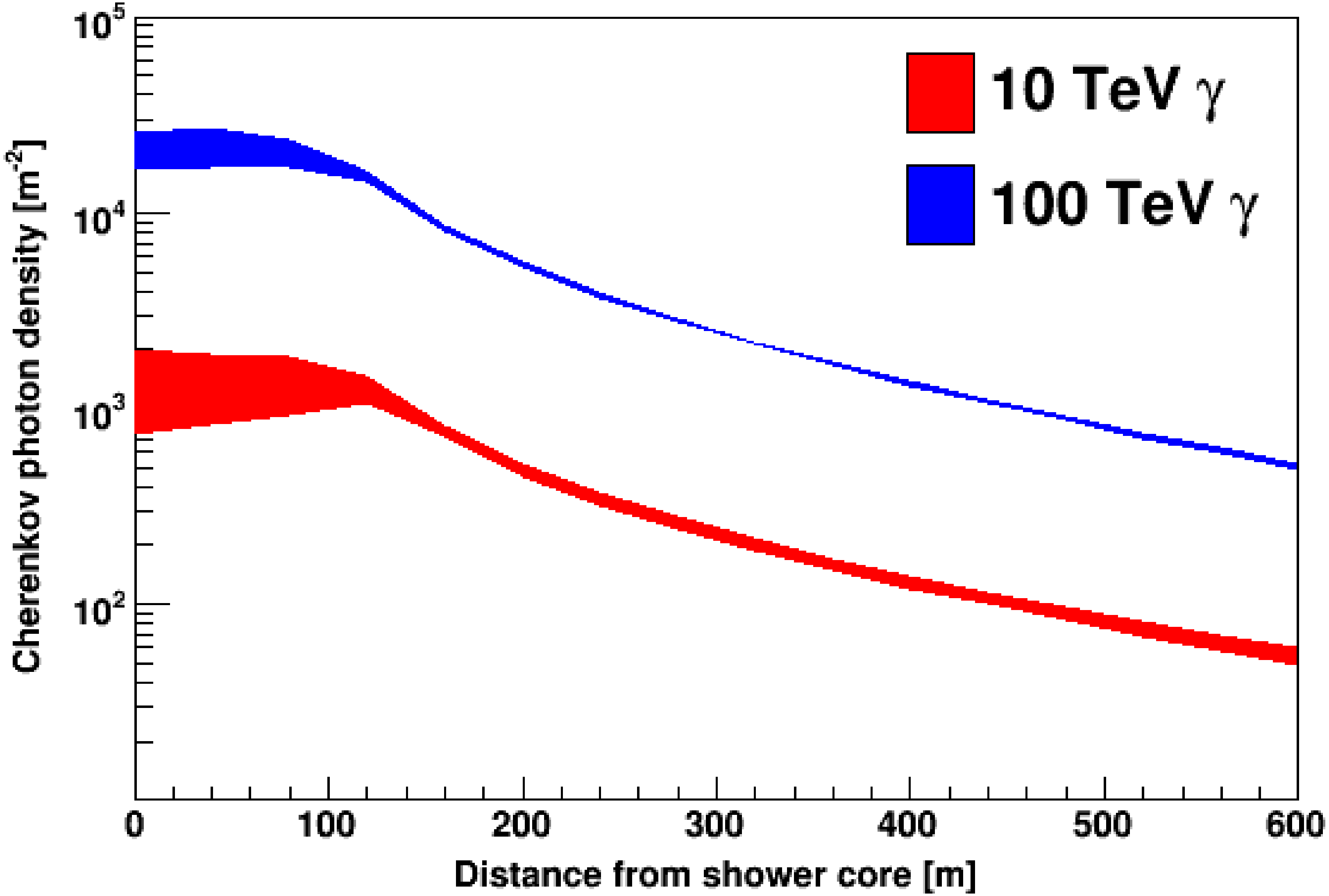
Sensitivity goal: better than 10^{-12} erg / cm^2 s

Concept:

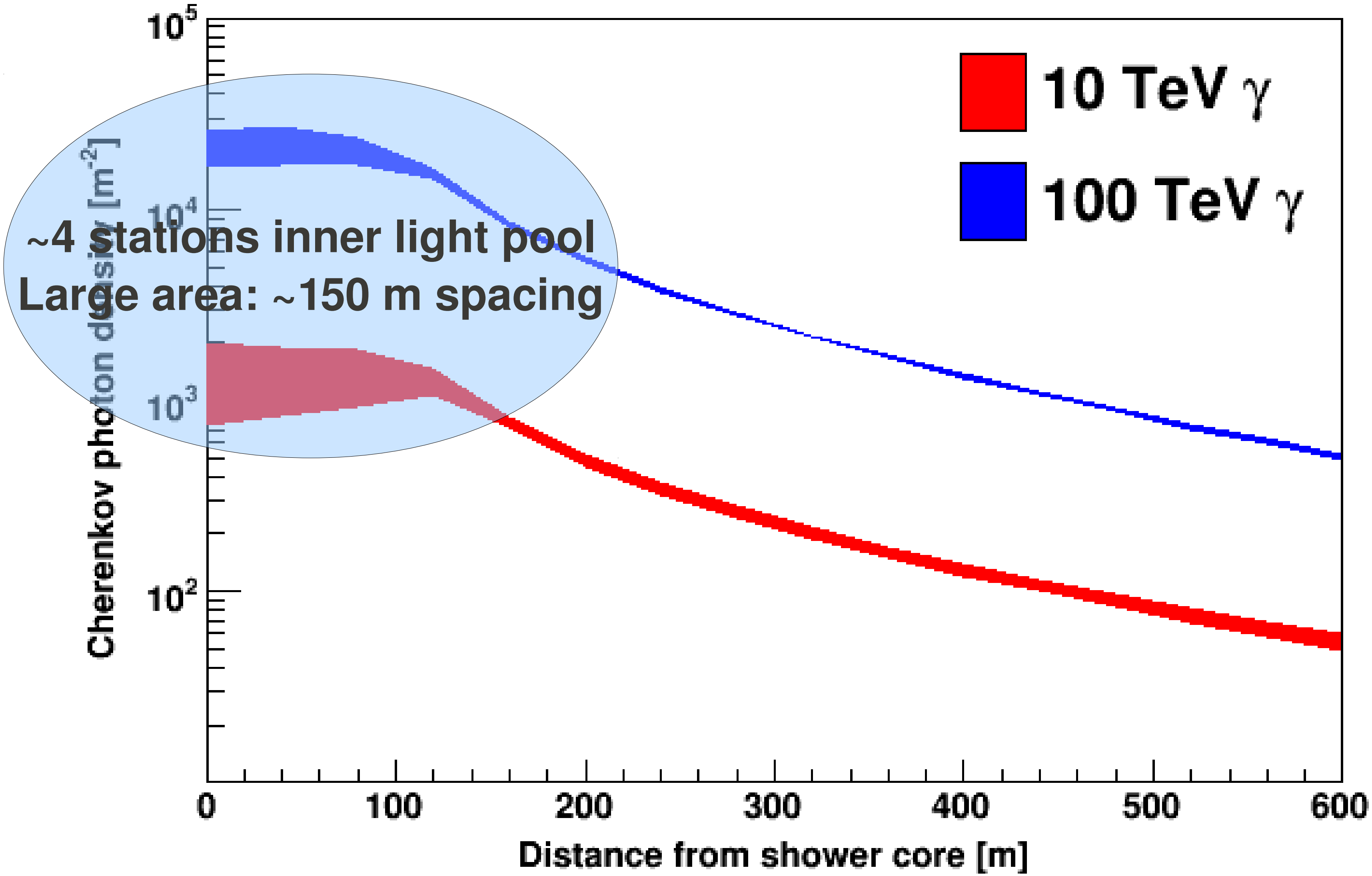
Very large effective area, wide field of view

Non-imaging atmospheric Cherenkov technique

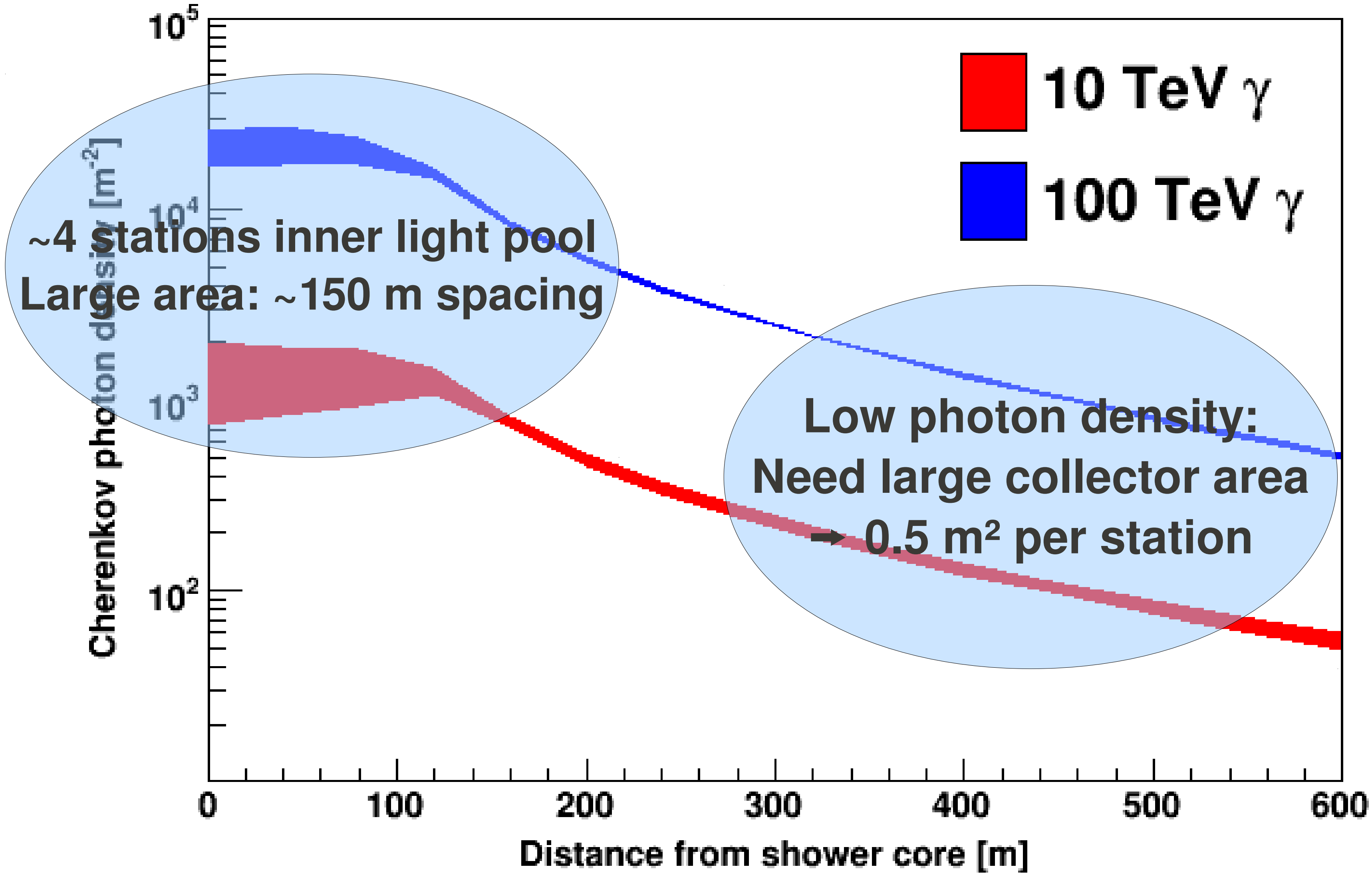
Lateral Cherenkov Photon Distribution



Lateral Cherenkov Photon Distribution



Lateral Cherenkov Photon Distribution



The HiSCORE principle

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

Imaging ACTs: > 10000 channels / km²

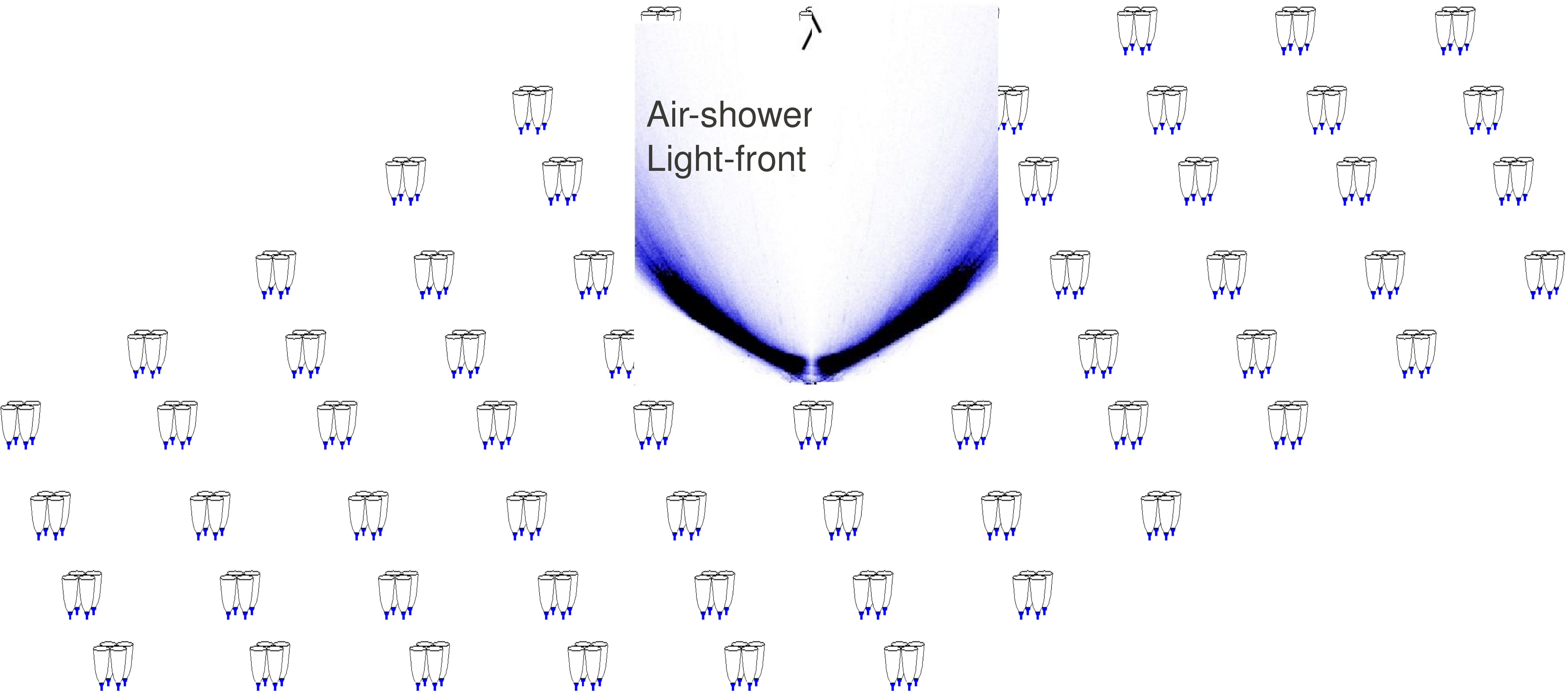
Non-imaging Cherenkov light-front sampling
SCORE: ~300 channels / km²

The HiSCORE principle

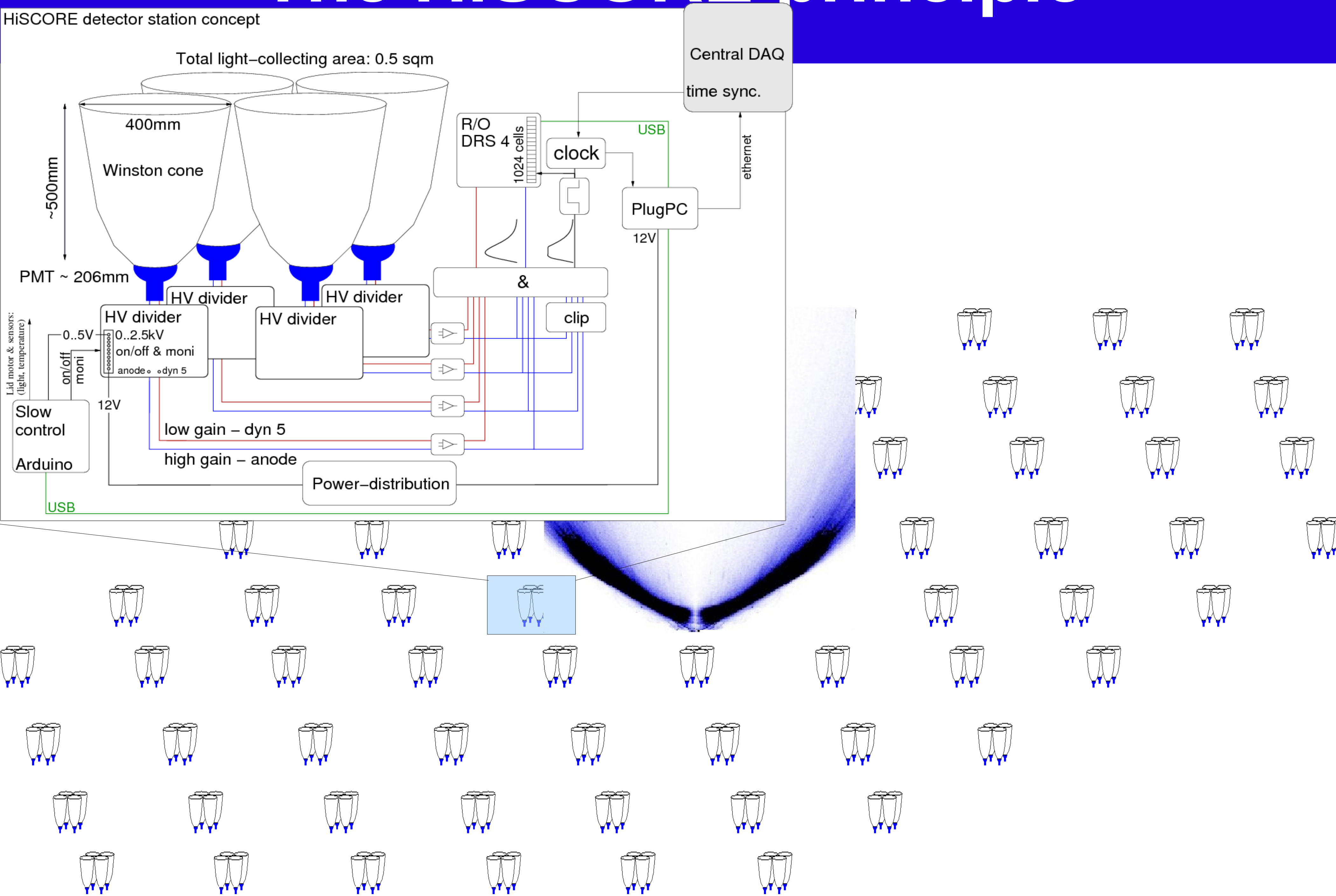
Ultra-High energy regime: **need large effective area !**

Imaging ACTs: > 10000 channels / km²

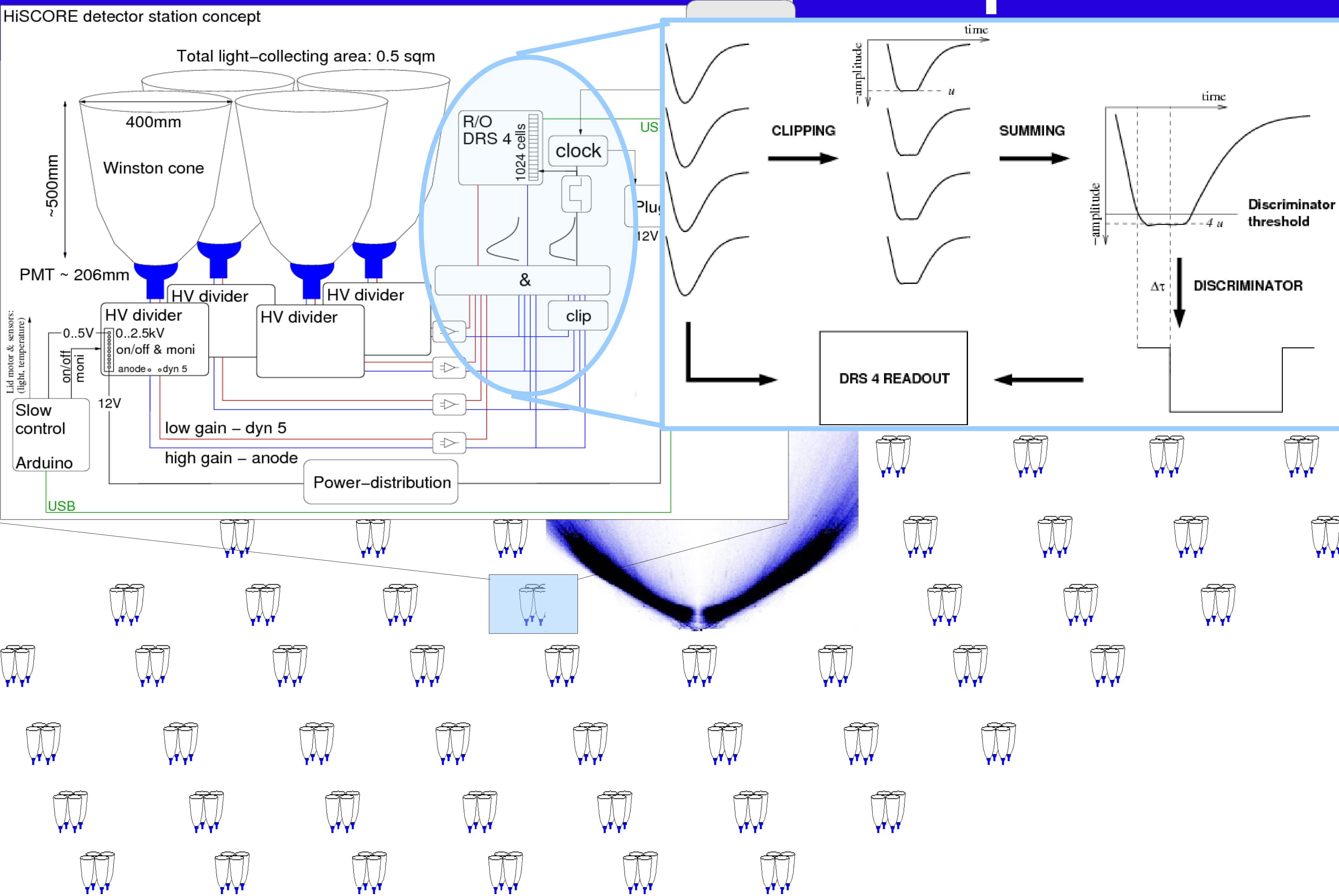
Non-imaging Cherenkov light-front sampling – record light amplitude and timing
SCORE: ~300 channels / km²



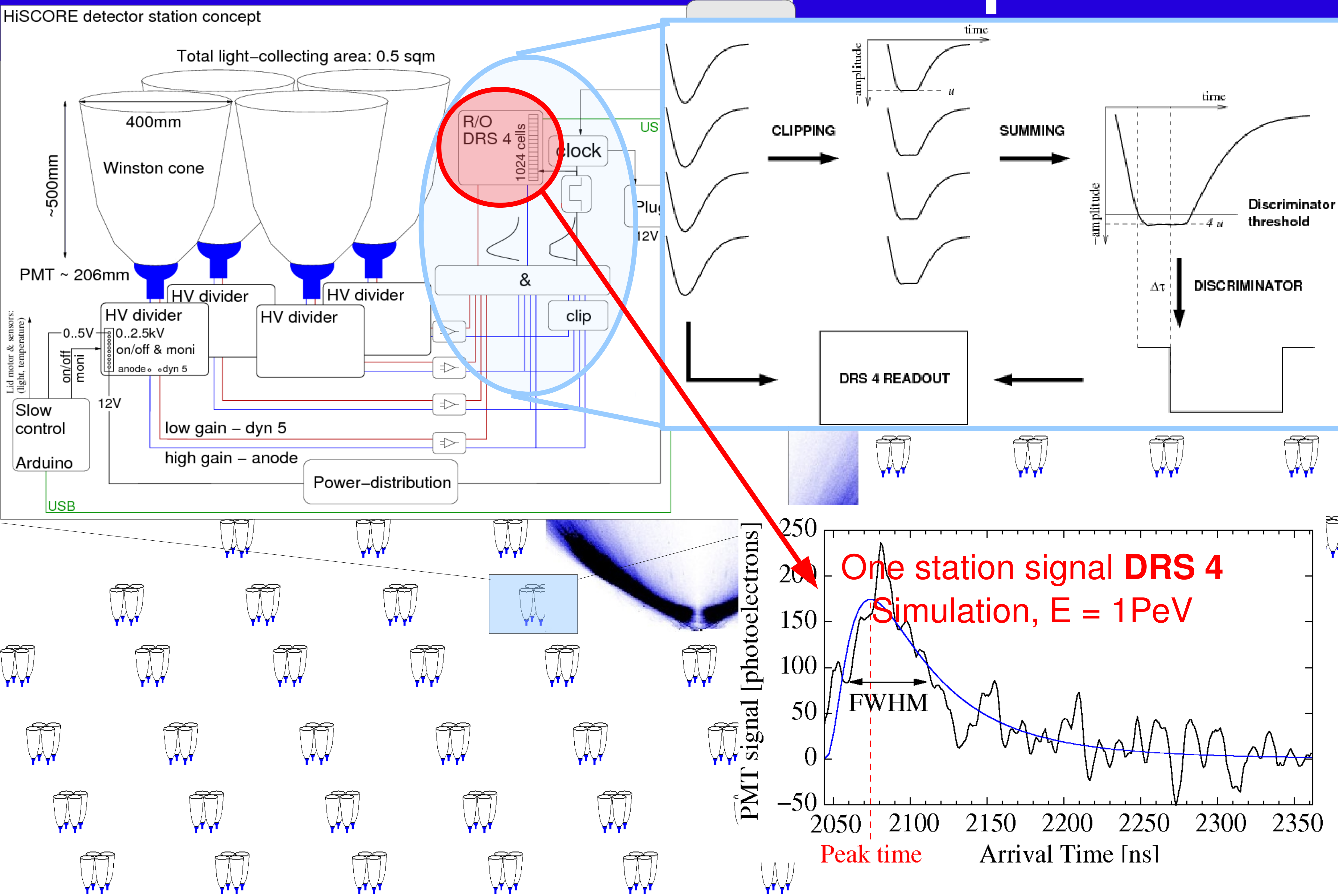
The HiSCORE principle



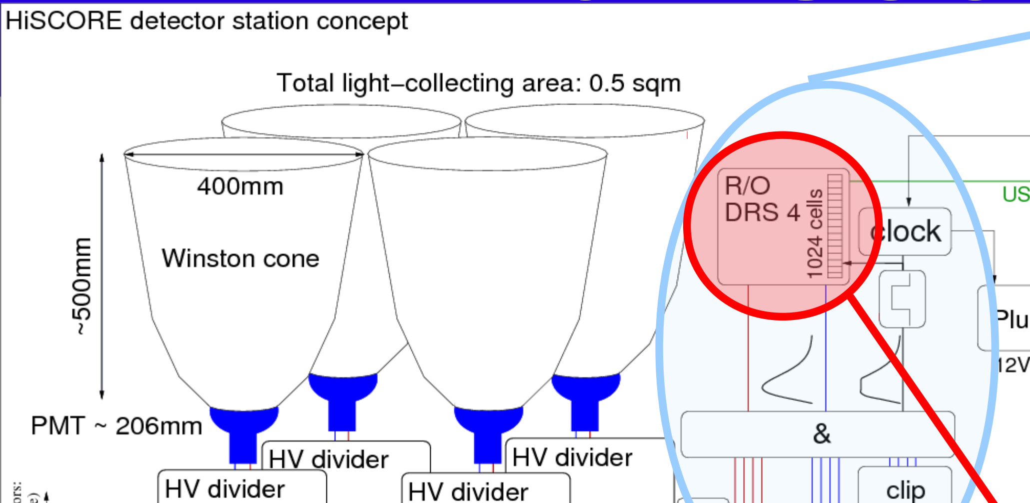
The HiSCORE principle

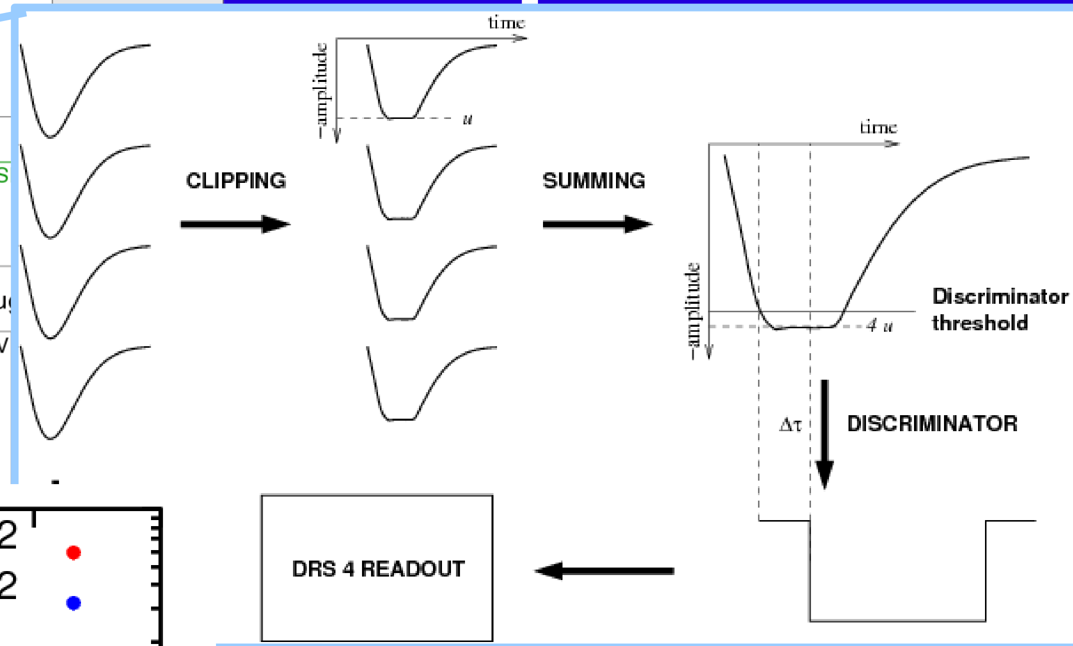


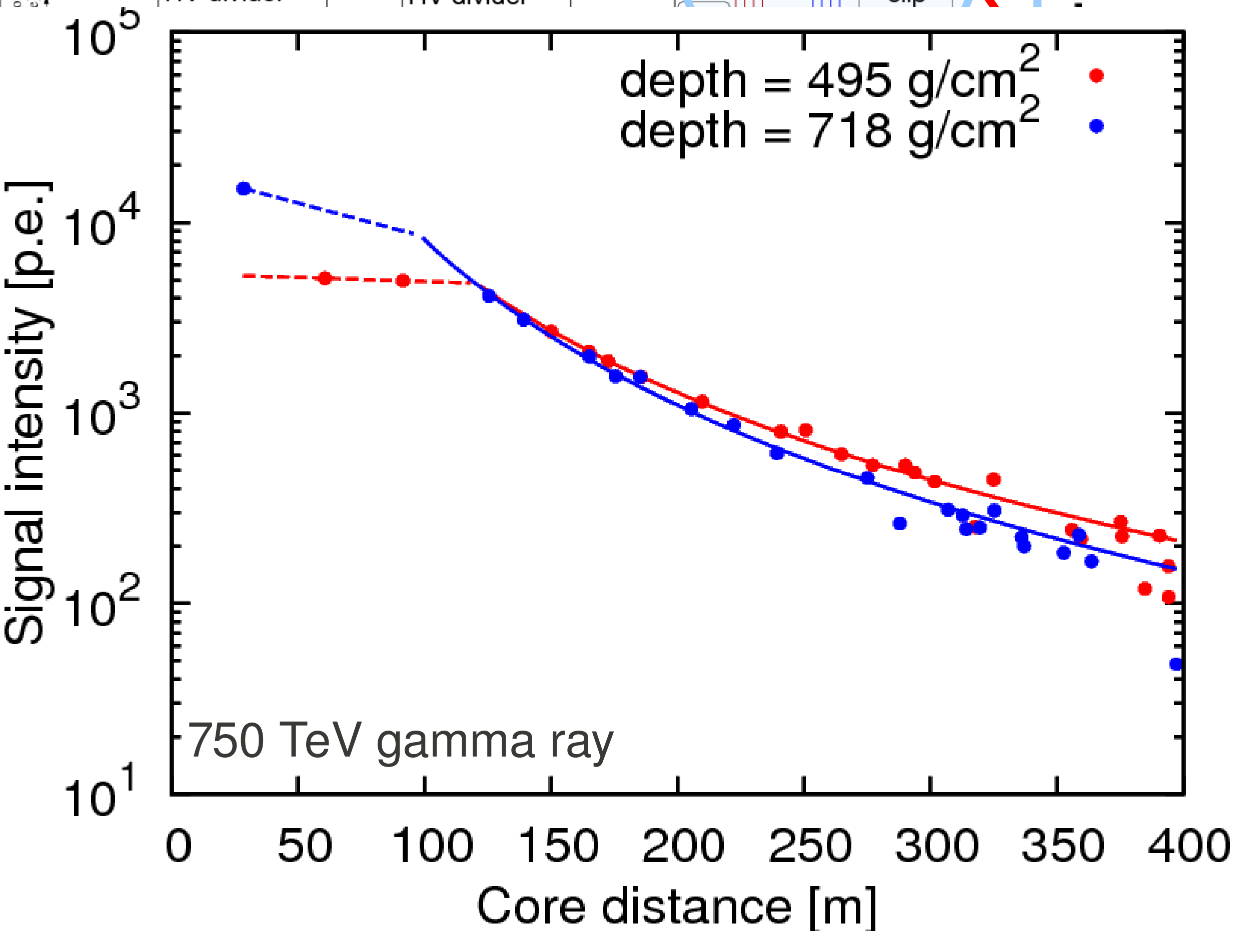
The HiSCORE principle

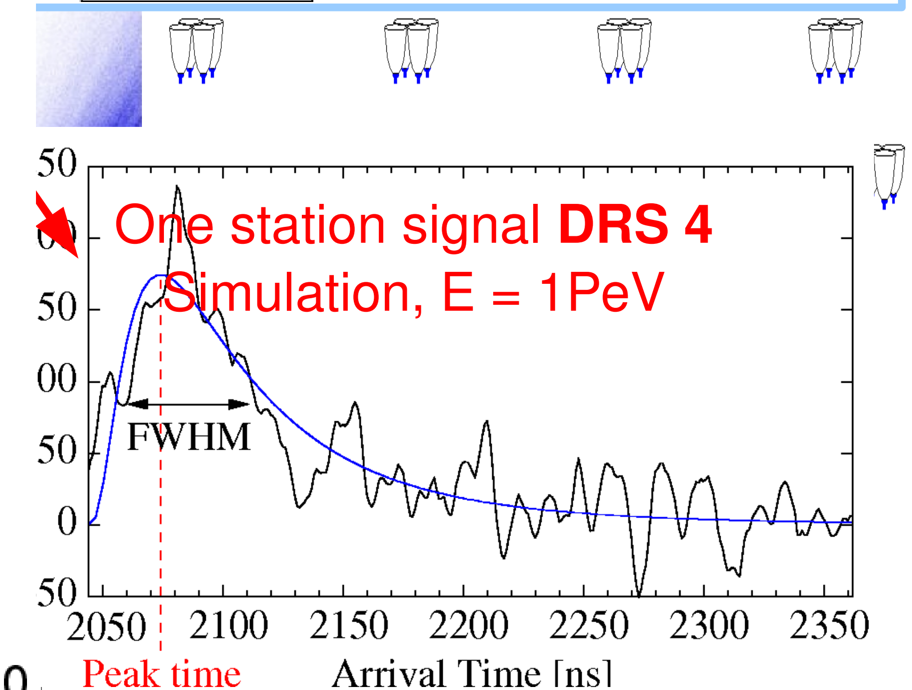


The HiSCORE principle









Shower simulation

Air-shower simulation CORSIKA 6735 [1]:

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

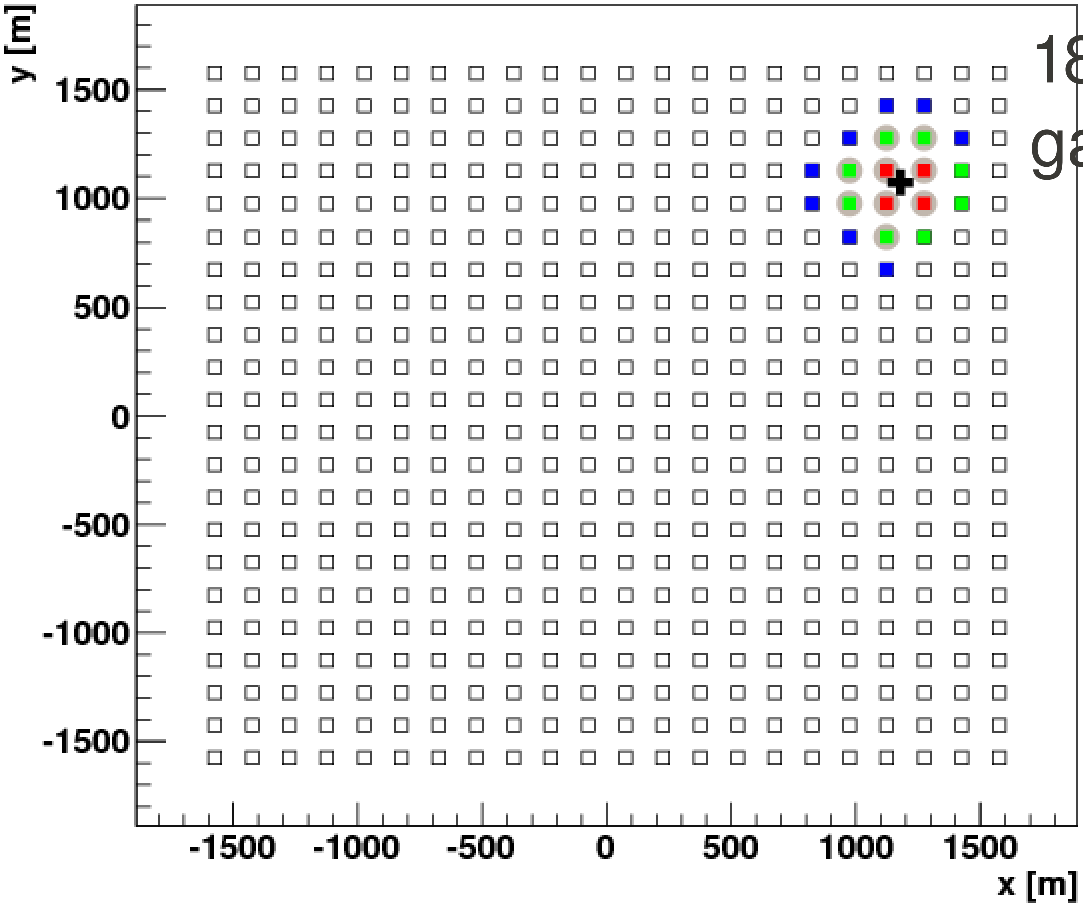
- Gamma, H, He, N, Fe
- 1/E powerlaw from 10 TeV (H: 5 TeV) to 5 PeV
- New production using Fluka planned

Detector simulation

Full detector simulation – sim_score [5]:

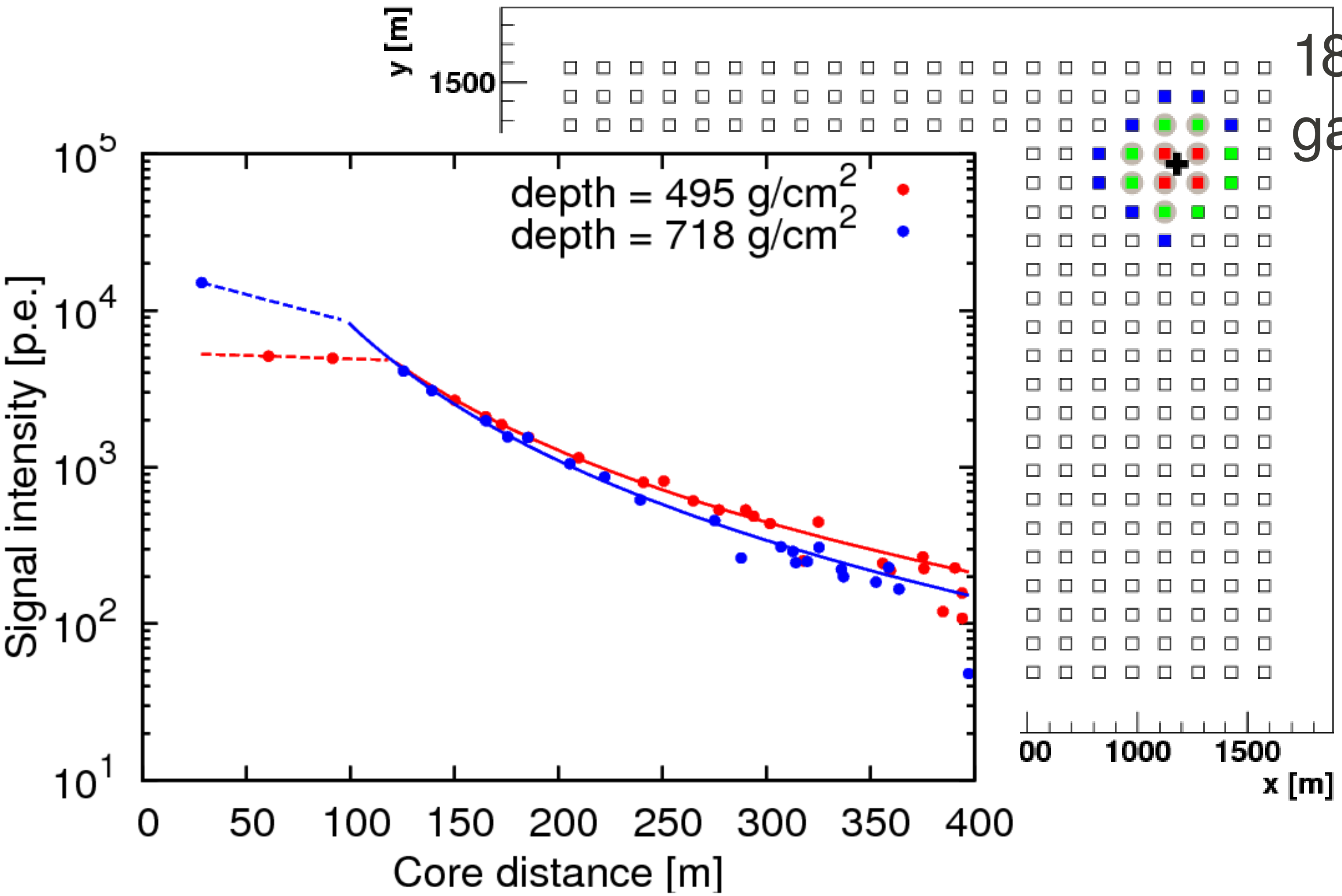
- Using iact package I/O routines, provided by [3]
- Winston cone acceptance included by ray-tracing simulation
- PMT quantum efficiency (Electron Tubes 8" PMT, data sheet)
- Electron collection efficiency
- PMT signal pulse-shape parameterization [4]
- Afterpulsing simulated w/ $P = 10^{-4}$ at 4 p.e.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

An event example



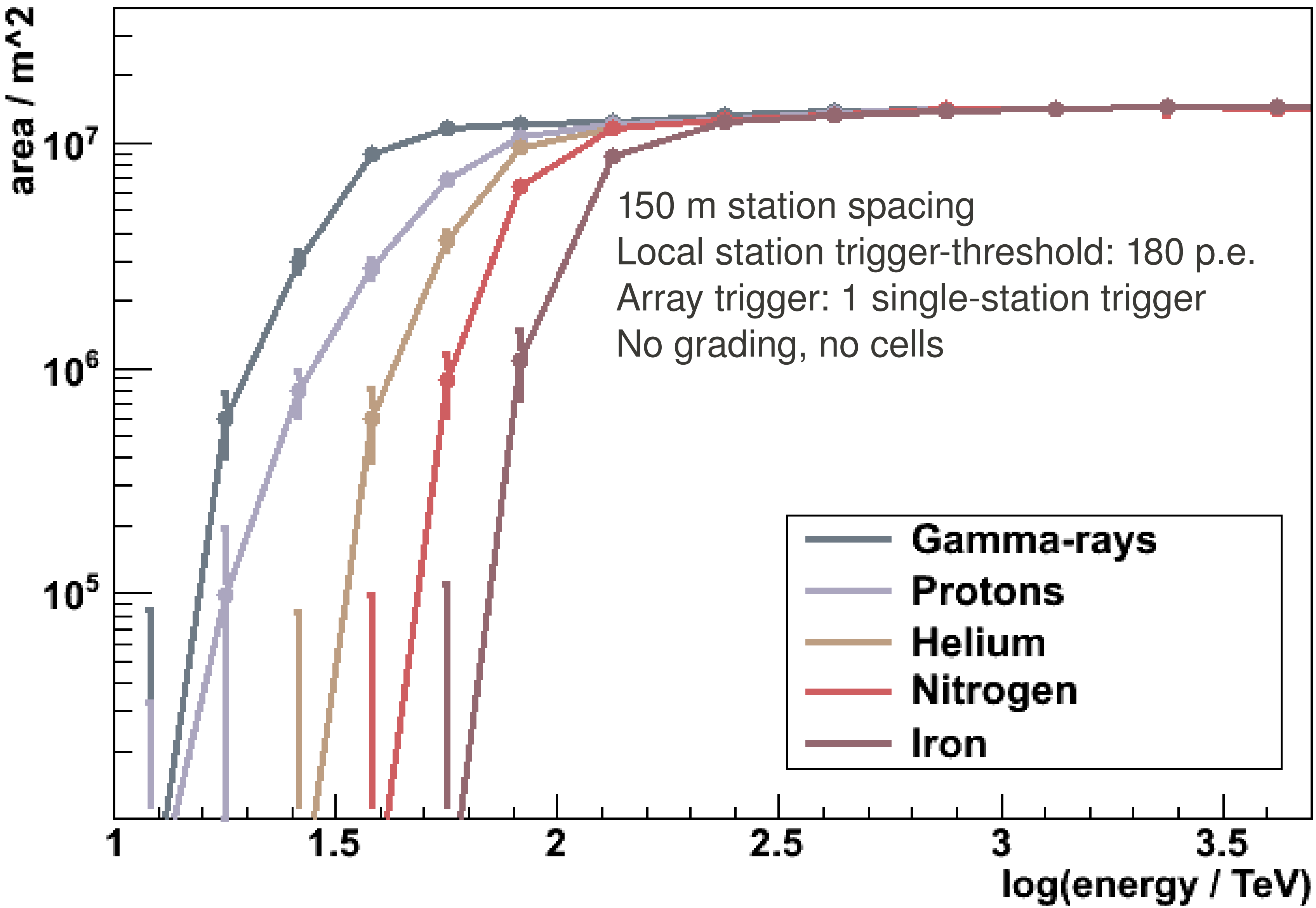
187 TeV
gamma-ray

An event example

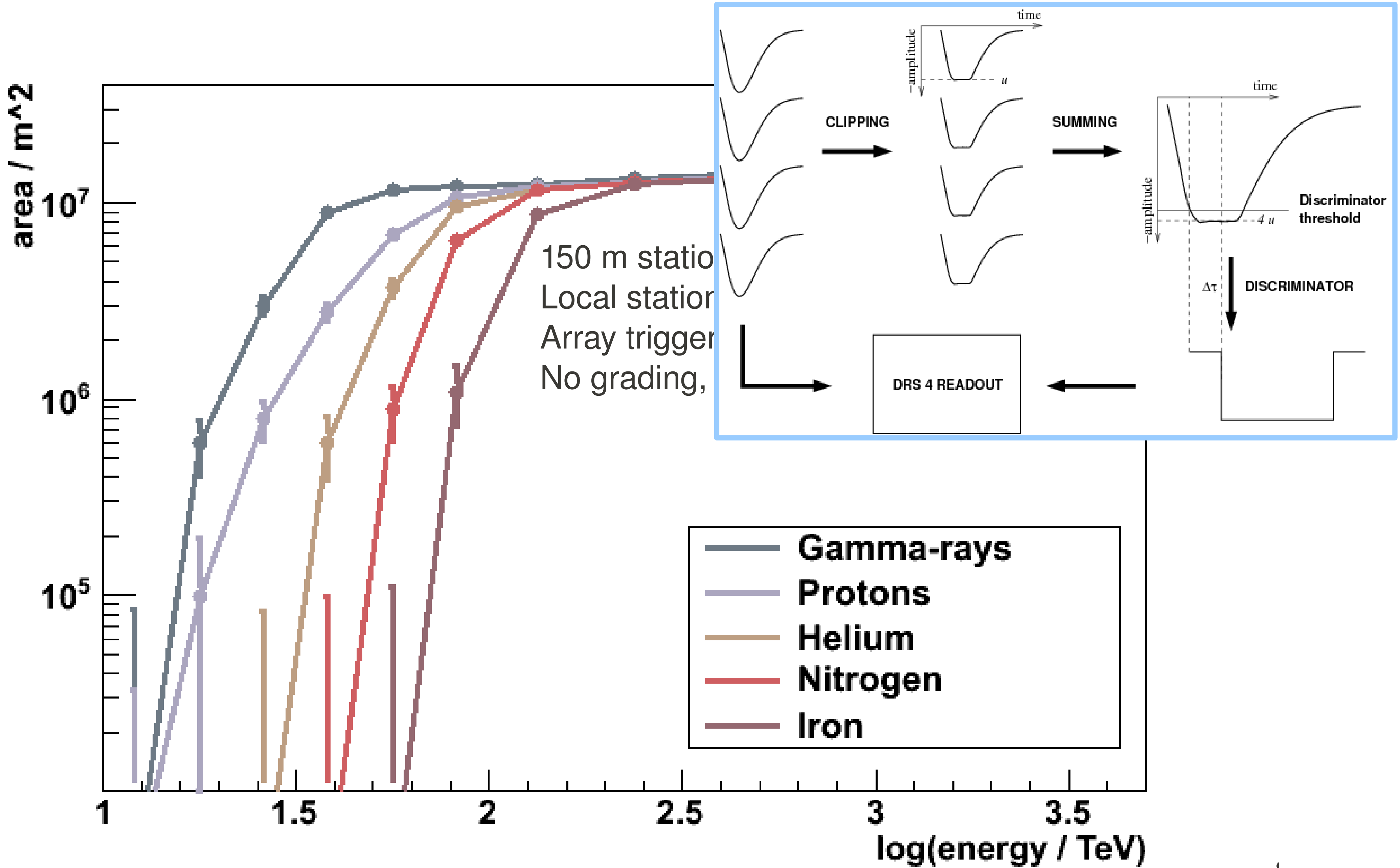


187 TeV
gamma-ray

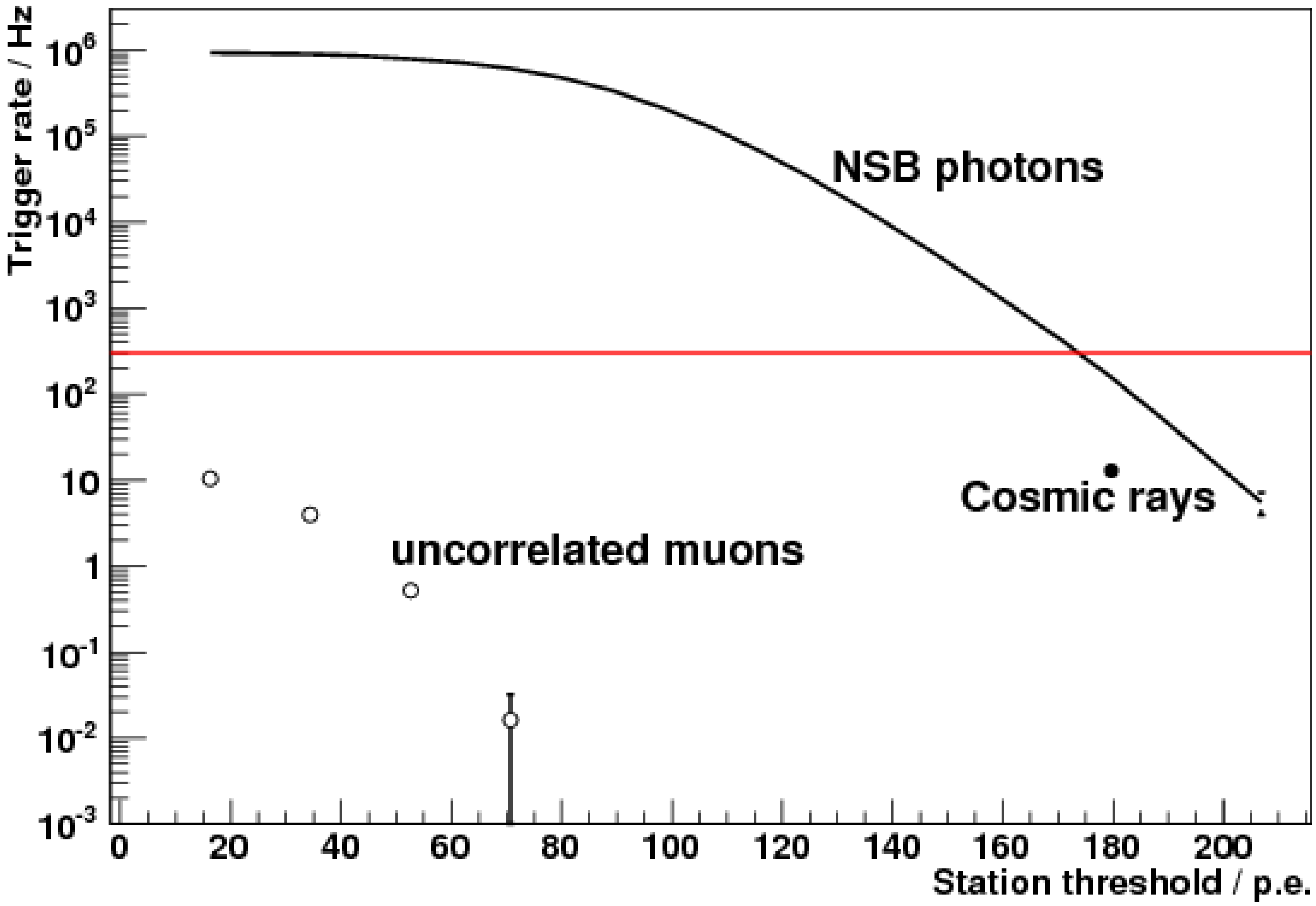
Effective CR trigger area



Effective CR trigger area



Trigger rates summary



Shower core reconstruction

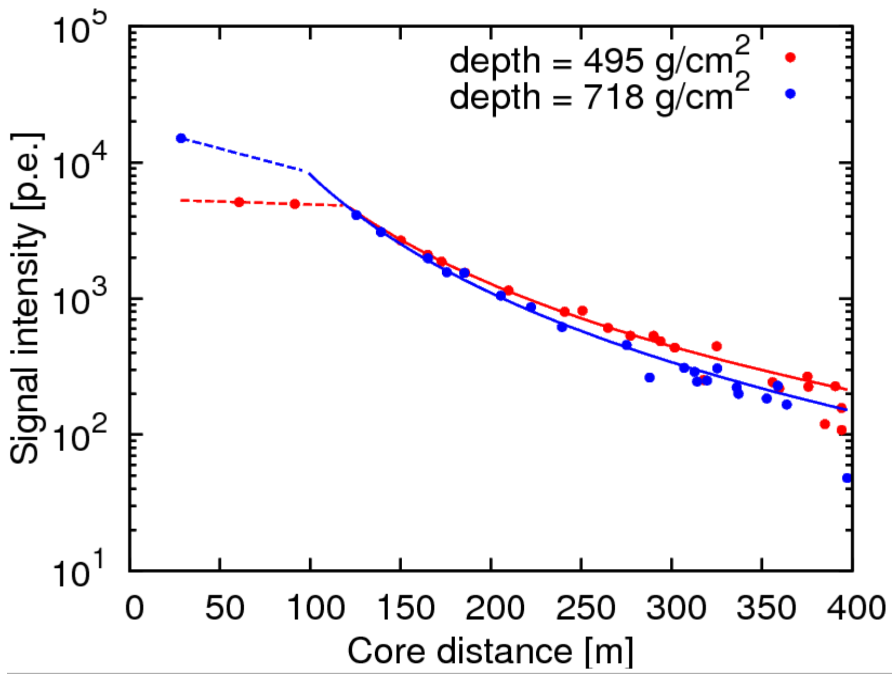
- Nstations < 5: weighted center of gravity
- Nstations >= 5 : Fit to LDF

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

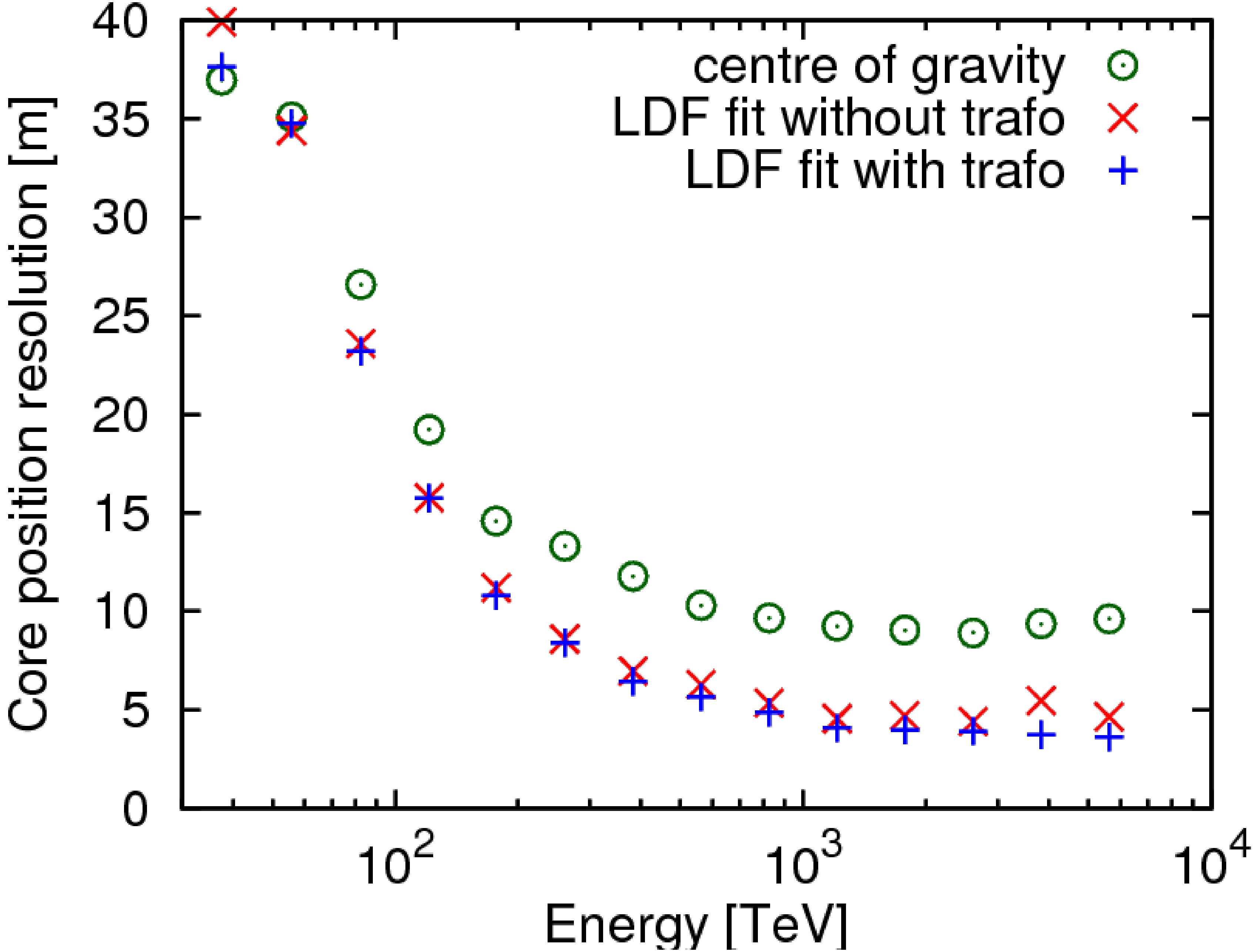
$$r = r(x,y) = \sqrt{x^2 + y^2}$$

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

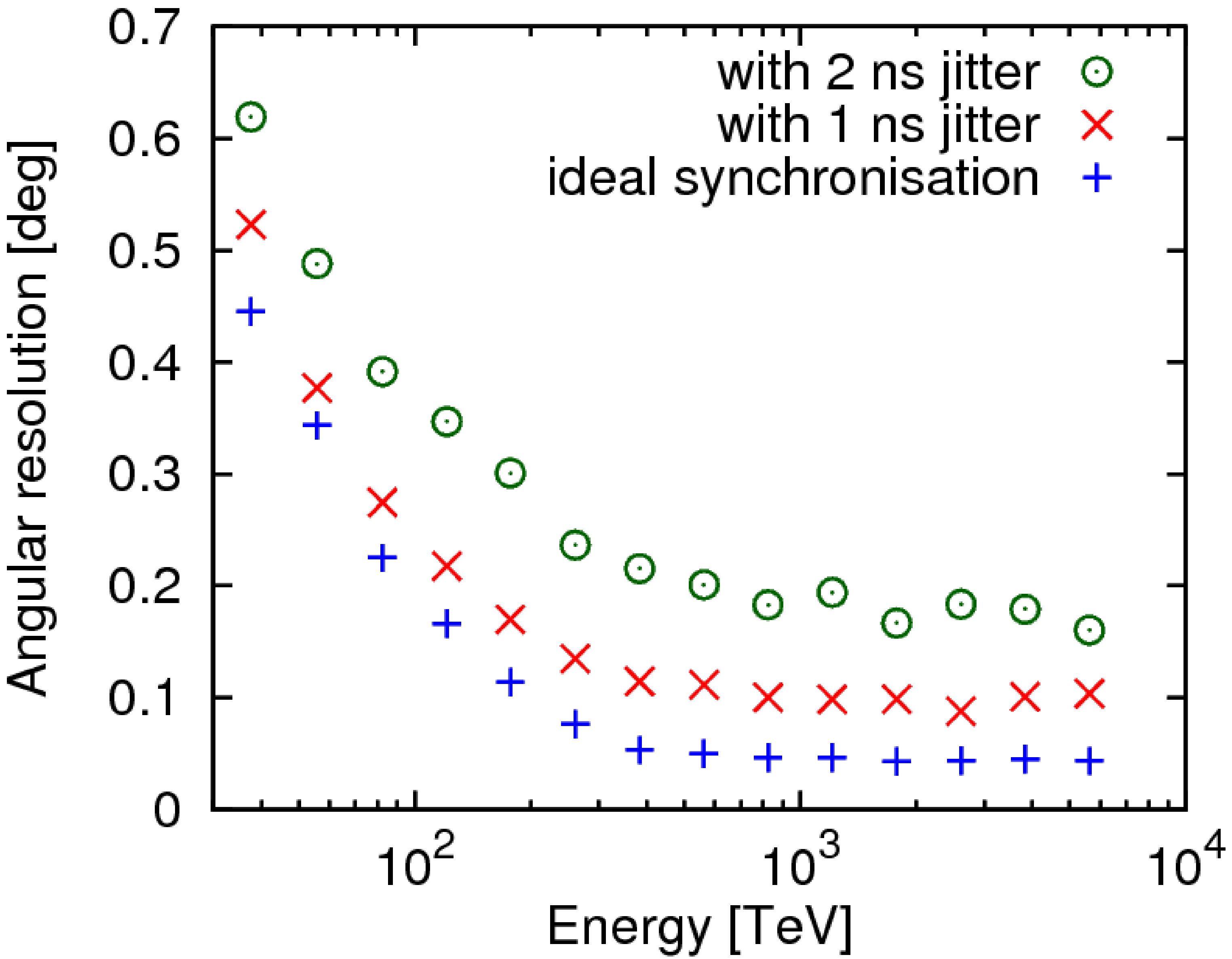
- Free parameters P, d, k, (x,y).
  Nstations >= 6: c_{LDF} free parameter
- To come:
  use width for outside showers



Shower core resolution

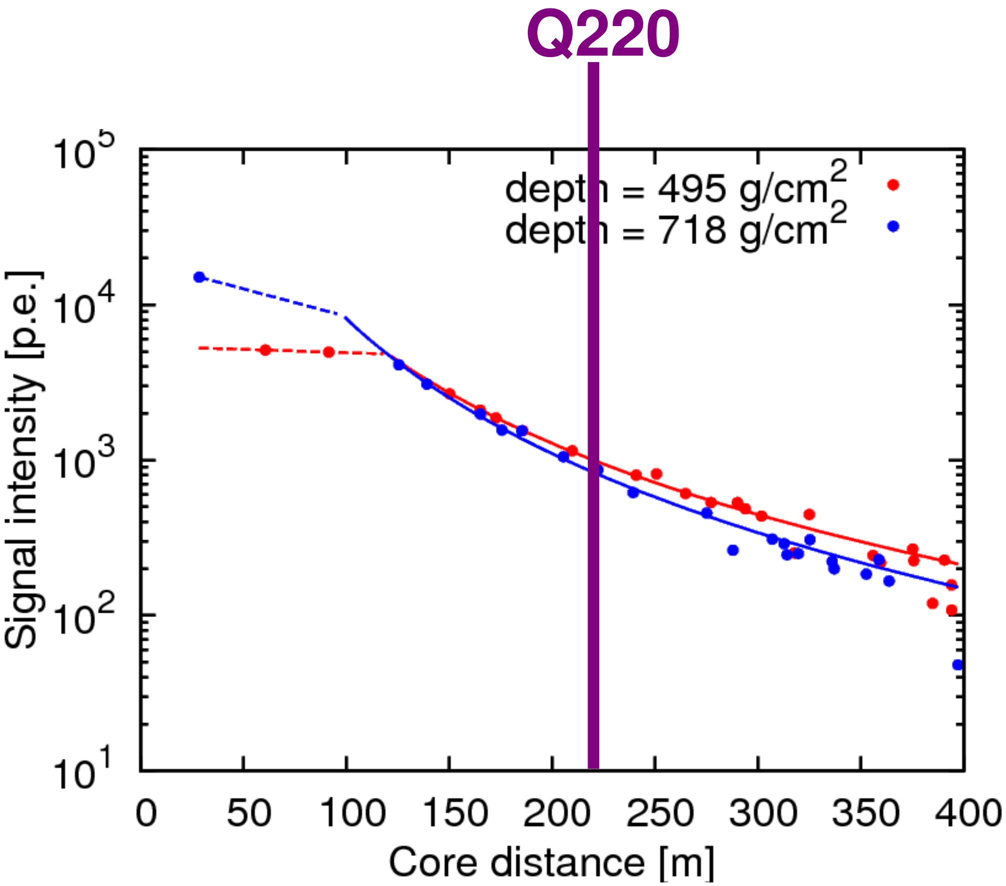


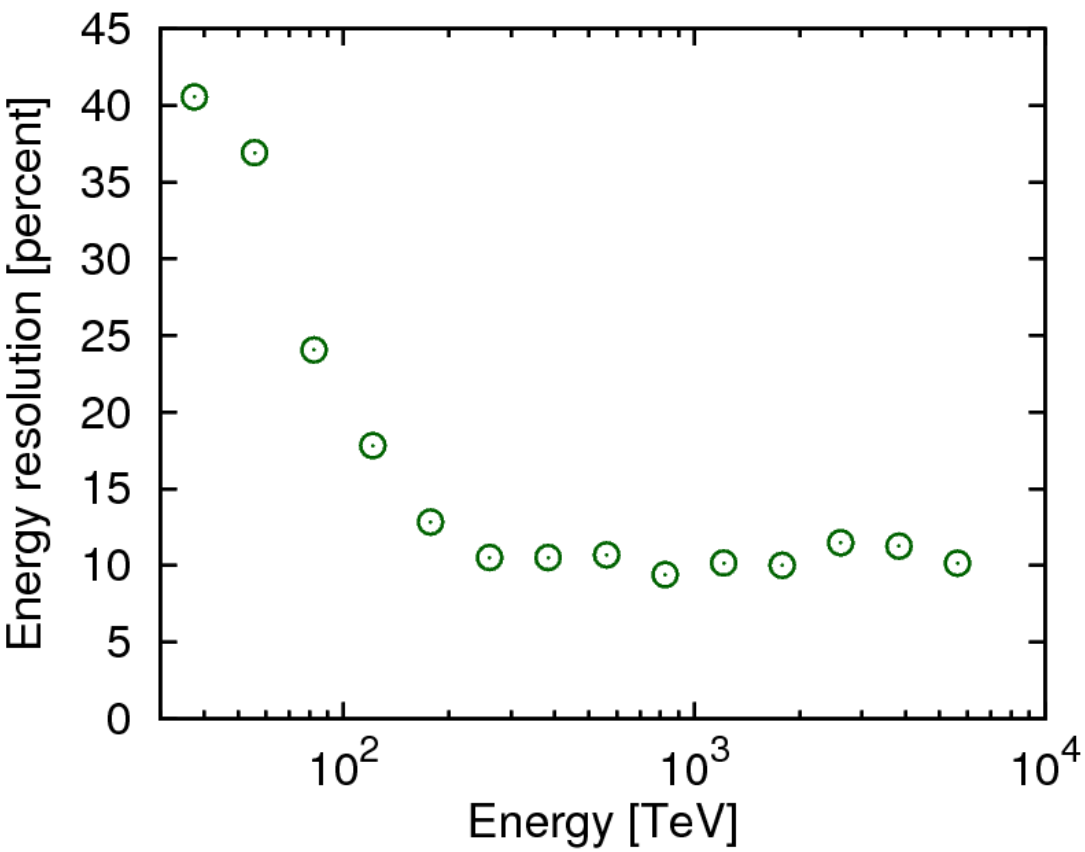
Angular resolution



Energy reconstruction

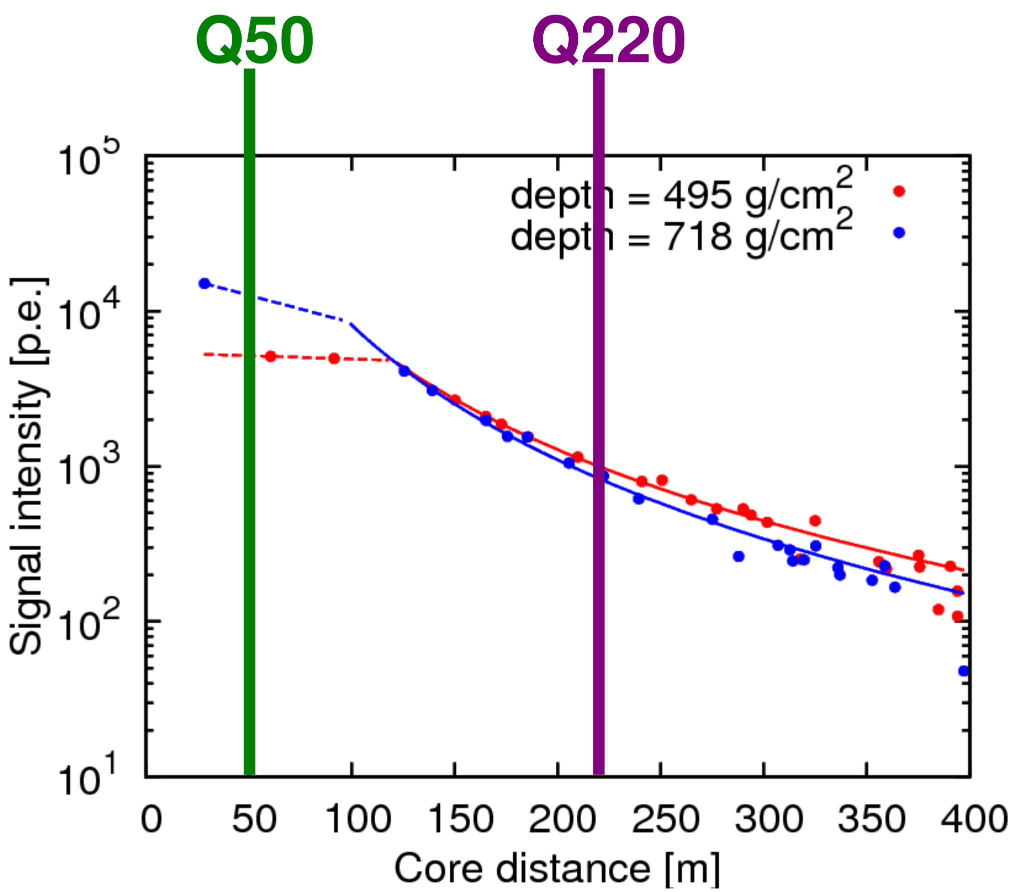
- Smallest impact of shower depth on photon density at 220m



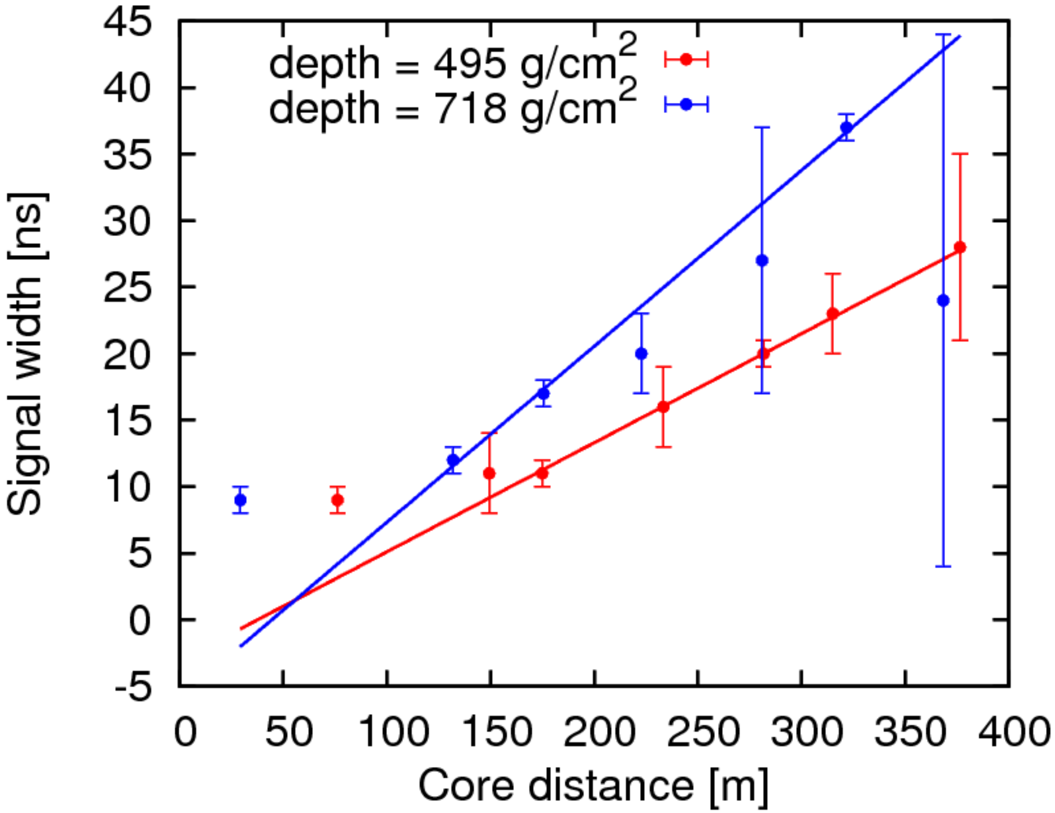


Shower depth reconstruction

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

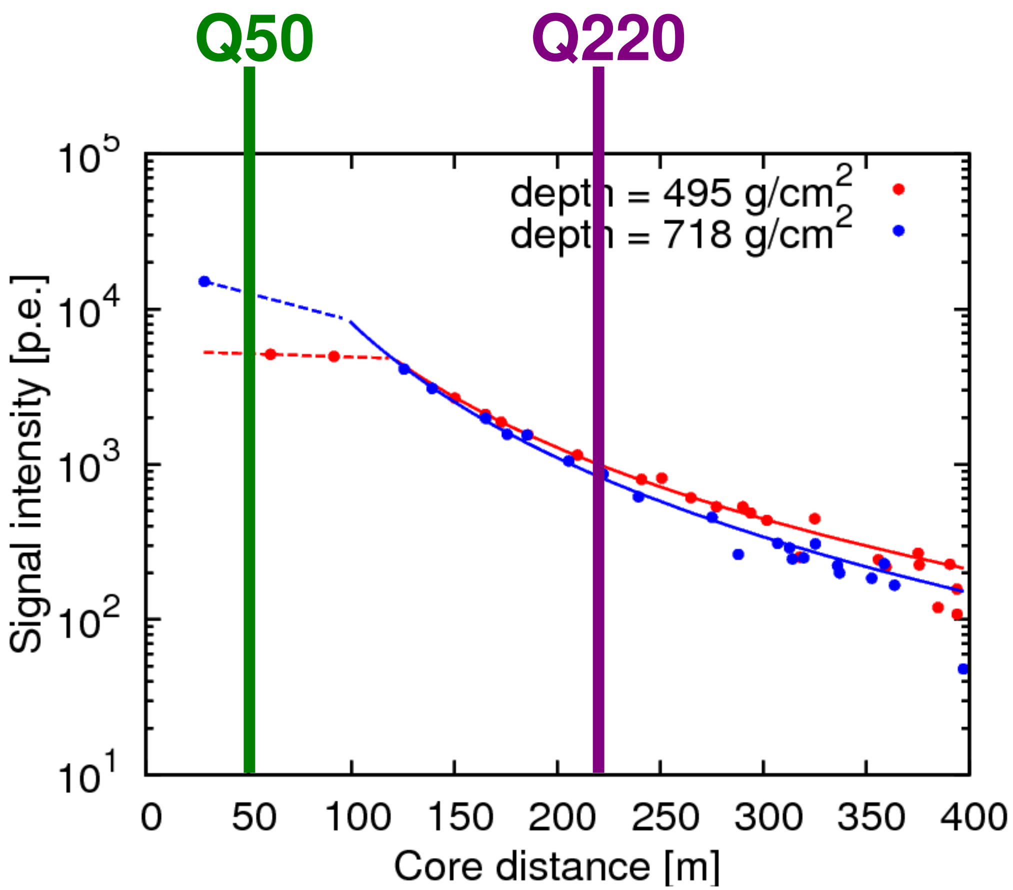


- **Dw:** Depth from signal width
- signal-stacking: add signals with same core-distance
- effective at core-distance > 150m



Shower depth reconstruction

- **Ds:**
  Depth from LDF slope: Q50/Q220



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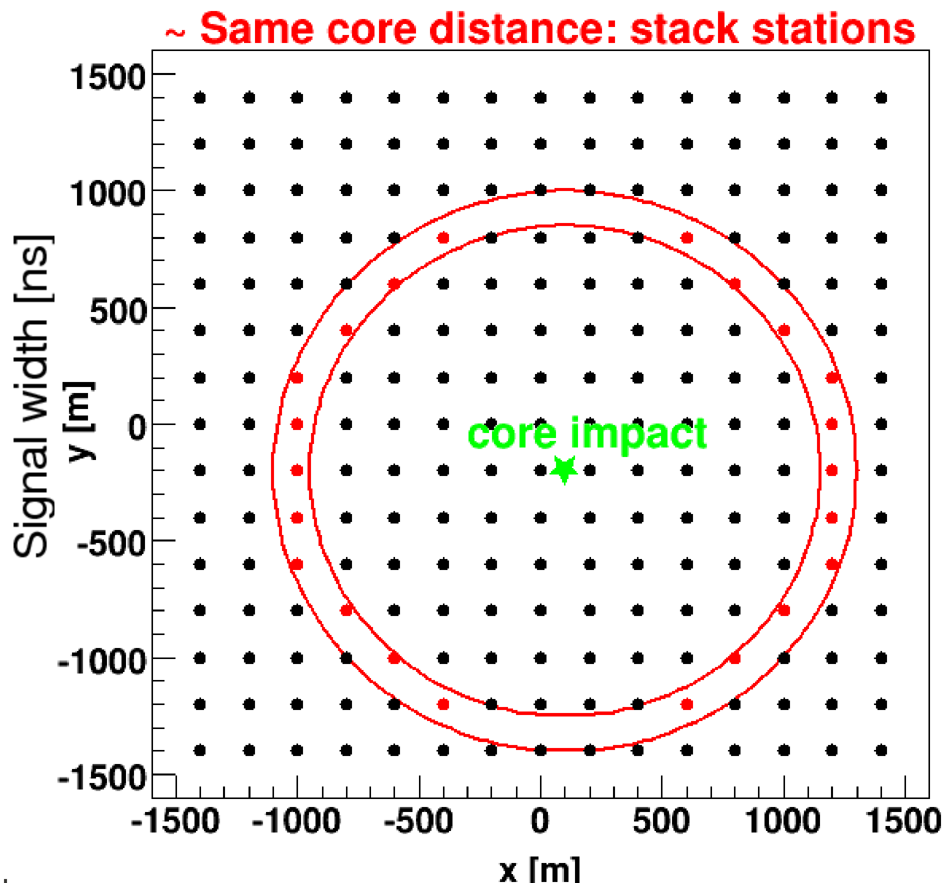
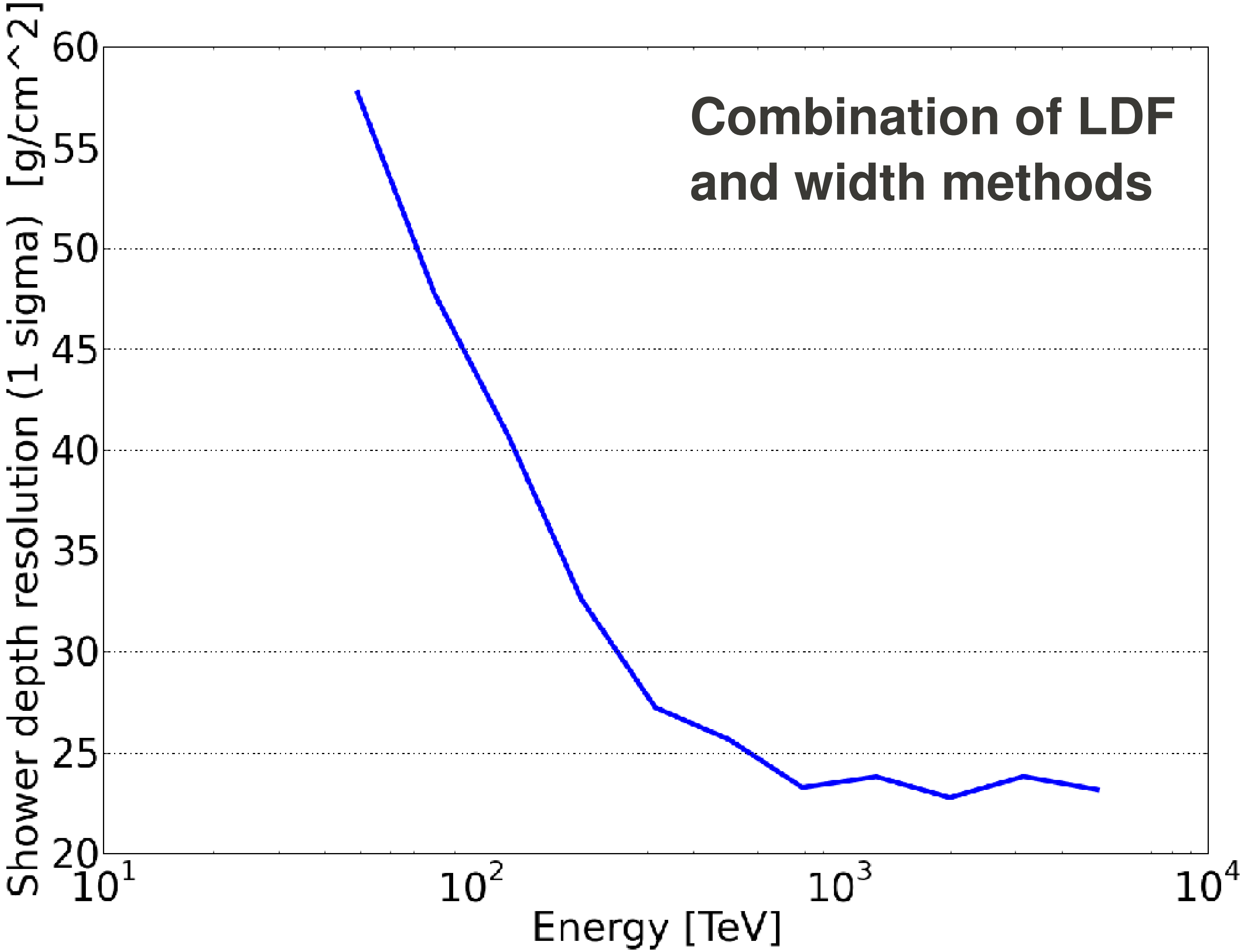


Shower depth resolution



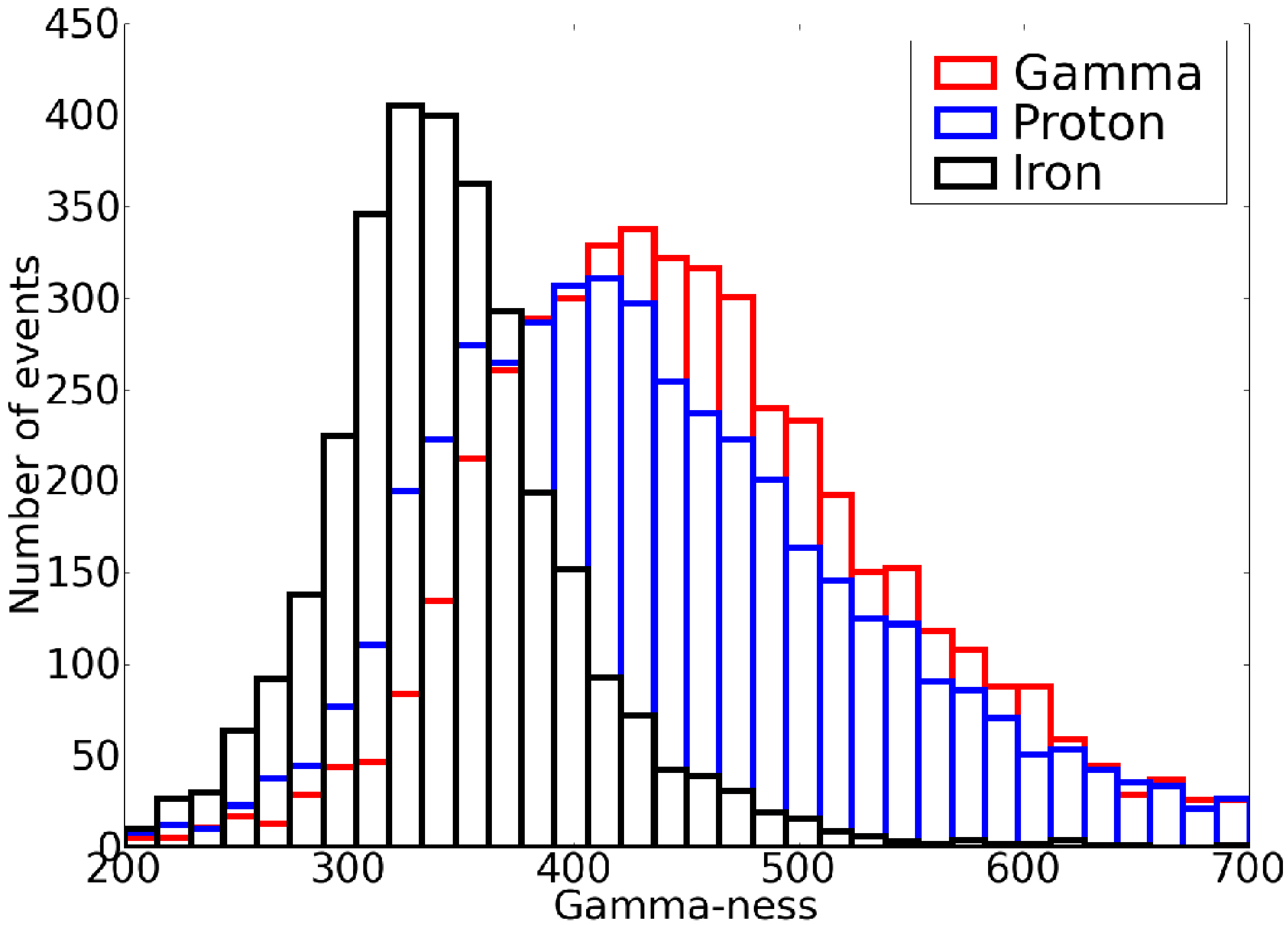
Particle identification

- Gamma-hadron separation
- Cosmic ray composition

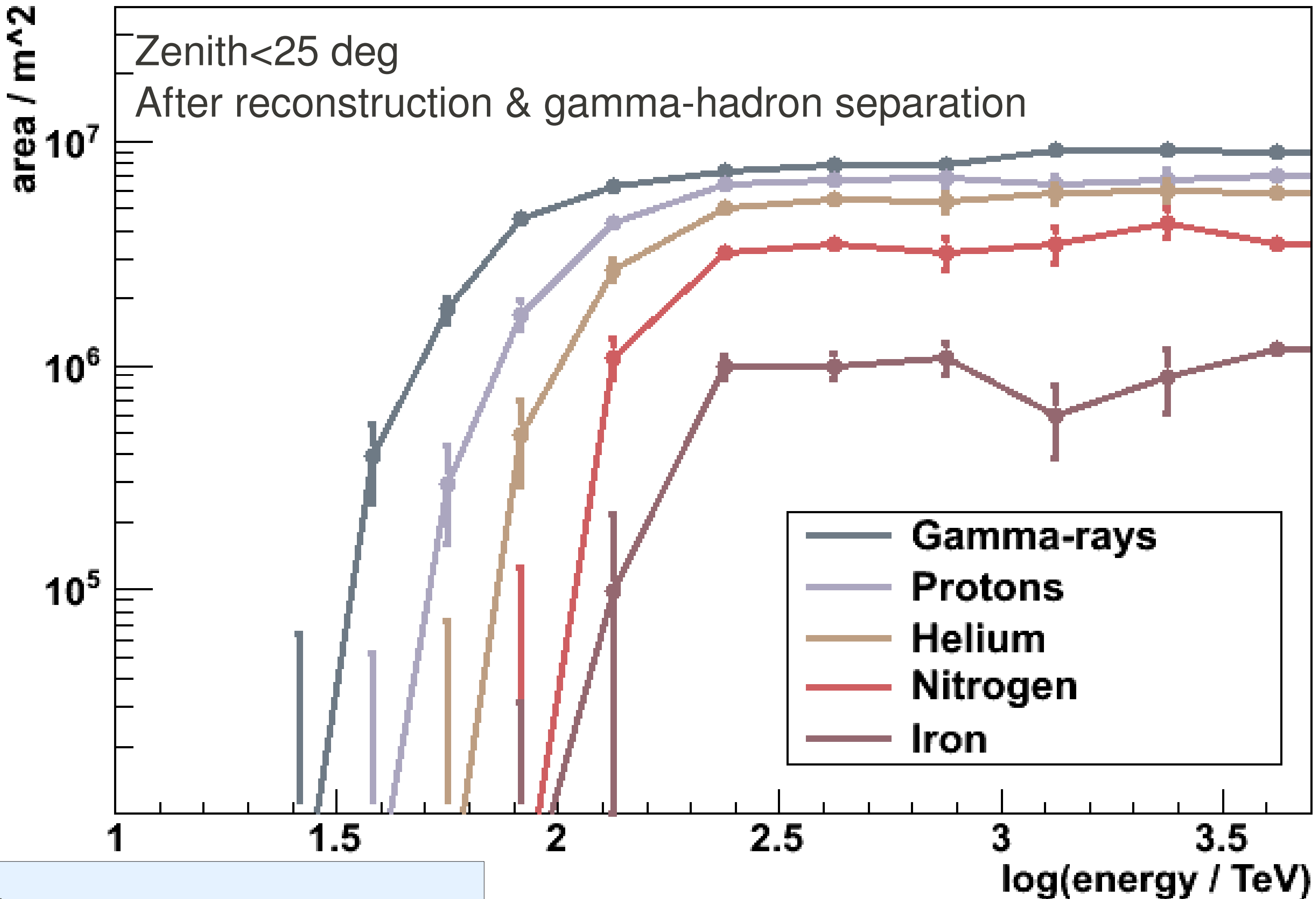
1) Shower depth depends on particle type
2) The signal width also depends on particle type
   - ➔ Systematic shift of depth estimate **Dw**
   - ➔ Separator: **Dw/Dq**

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

Particle identification

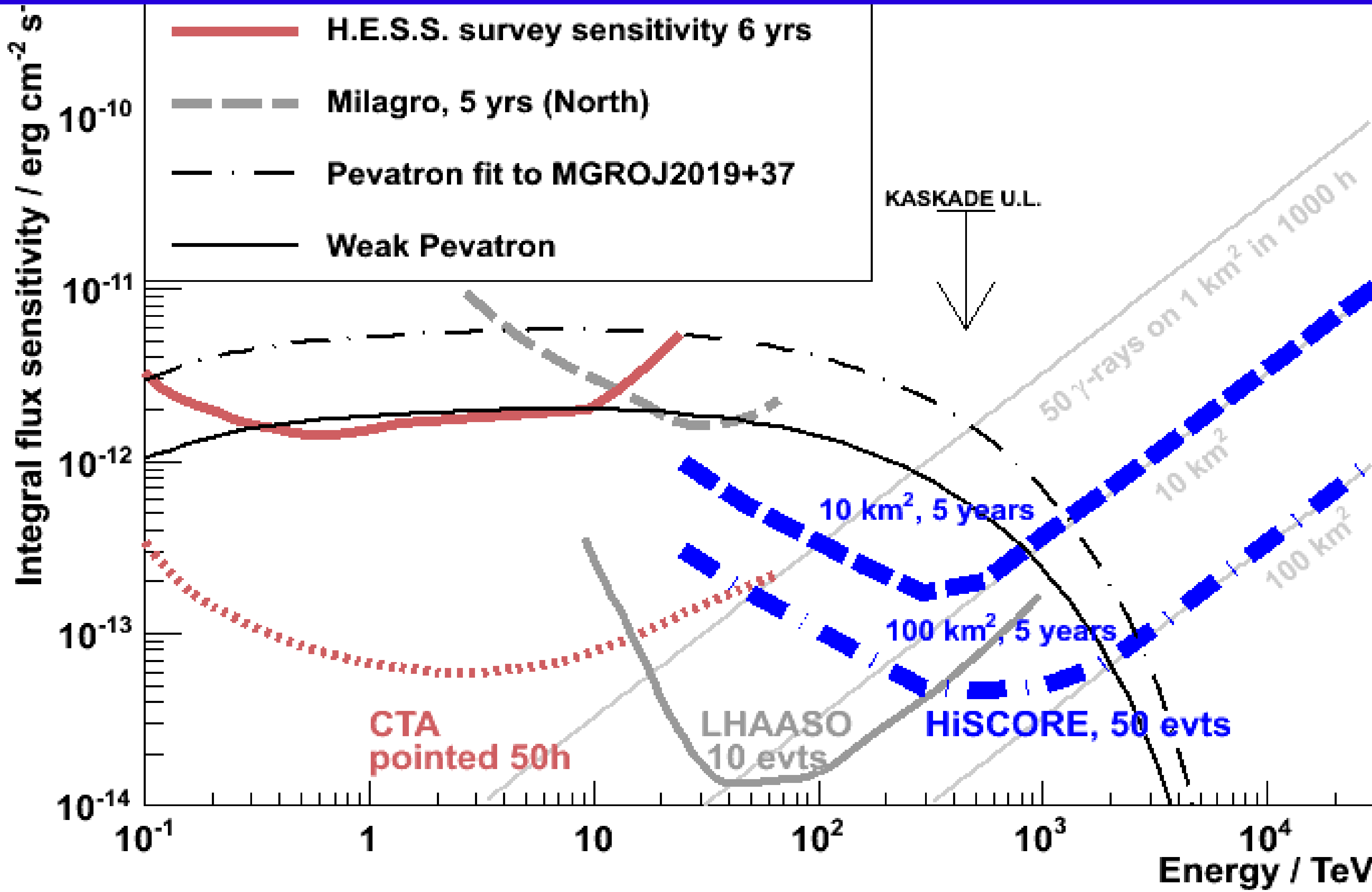


Effective area @ reconstruction level

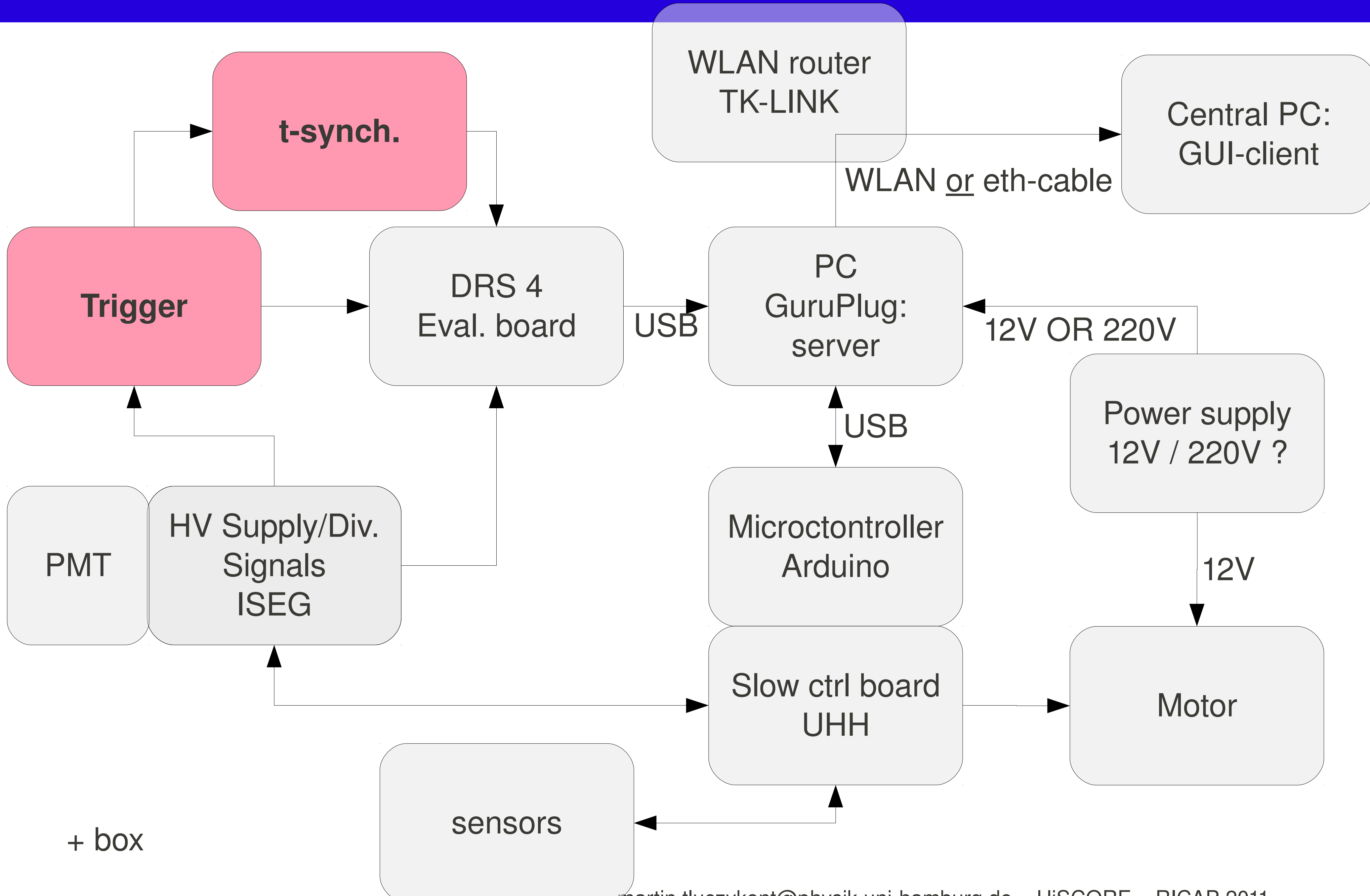


Reconstruction cuts:
- ≥ 3 triggered stations
- Contained reconstructed core impact position
- Separator ≥ 400

SCORE Sensitivity

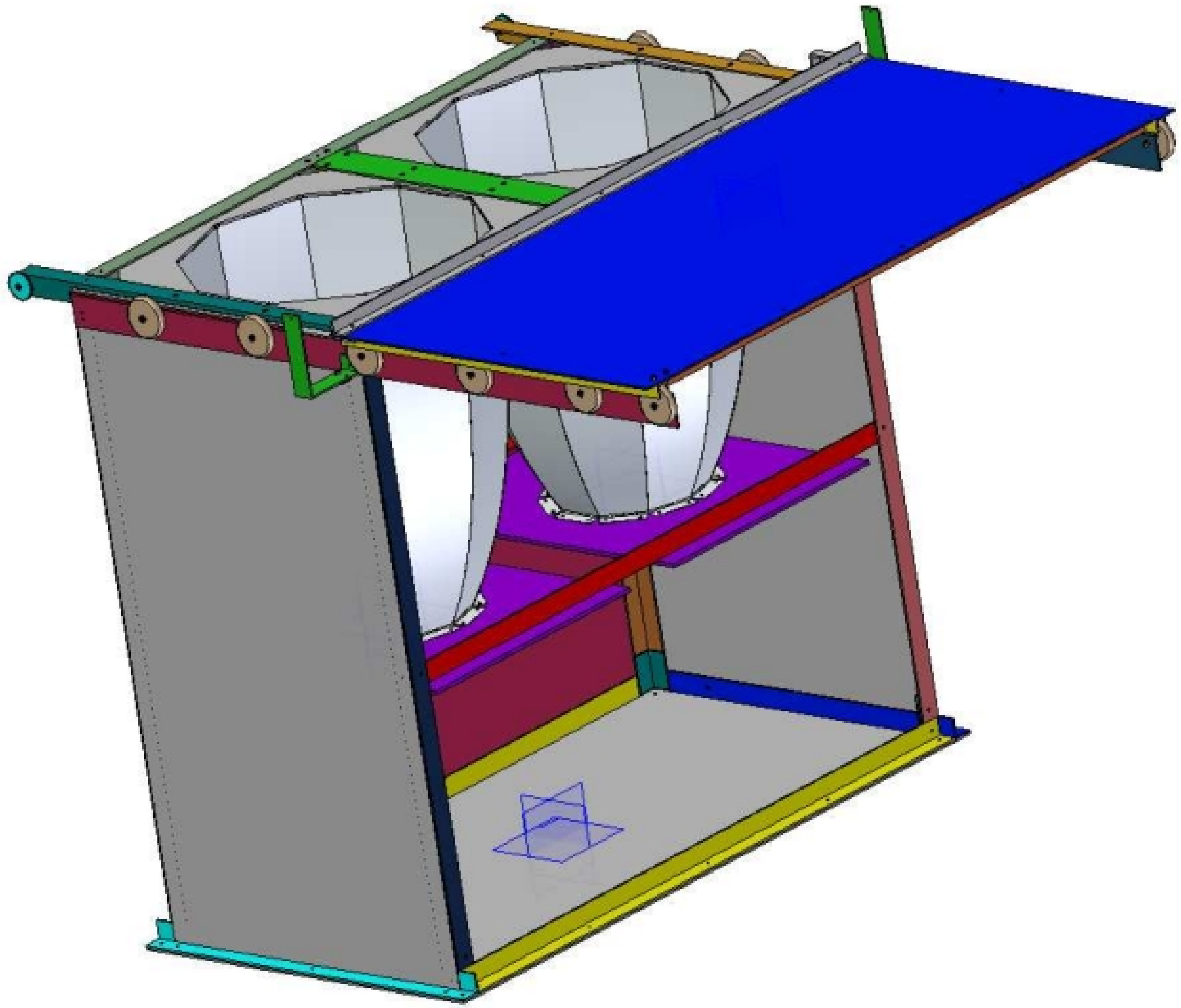


Hardware status

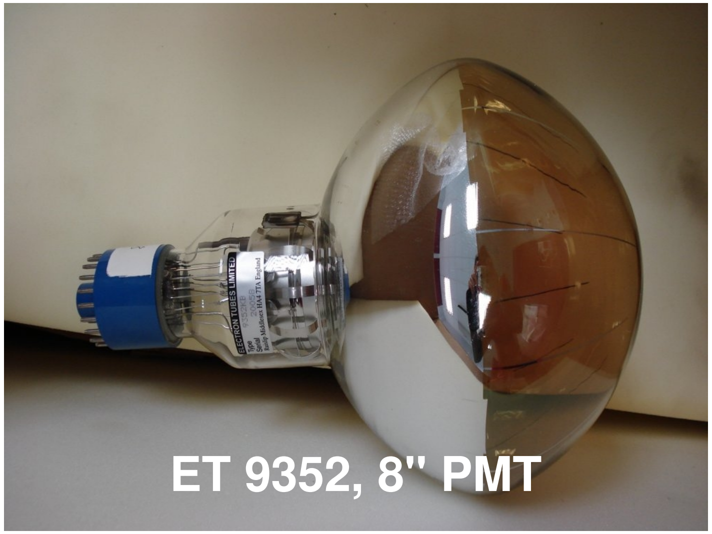


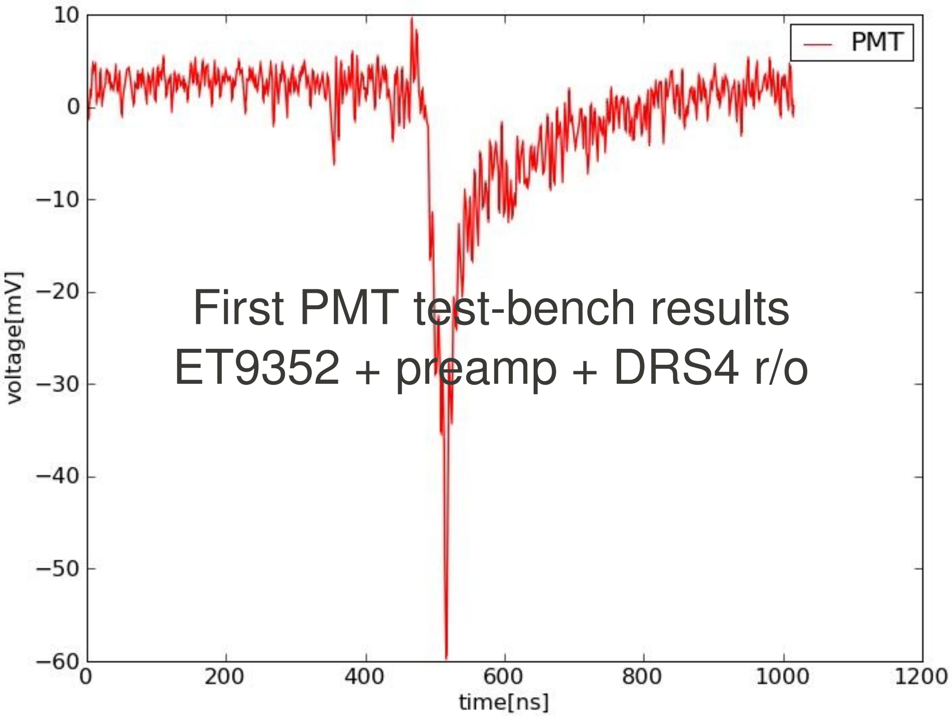
+ box

Mechanics

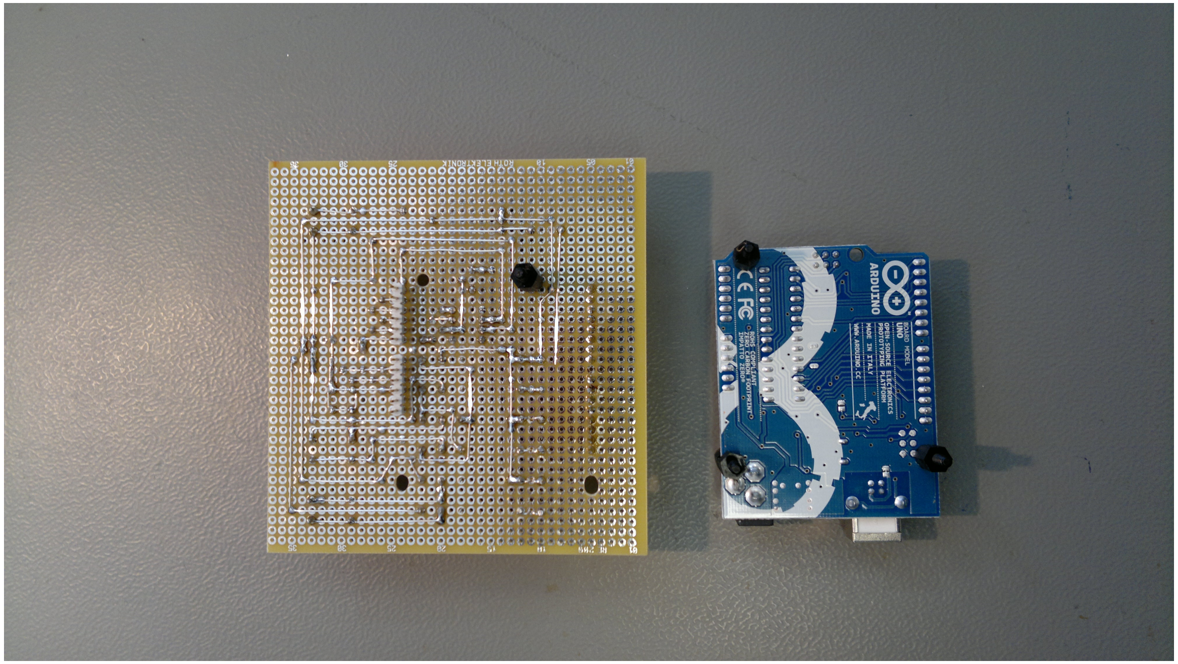


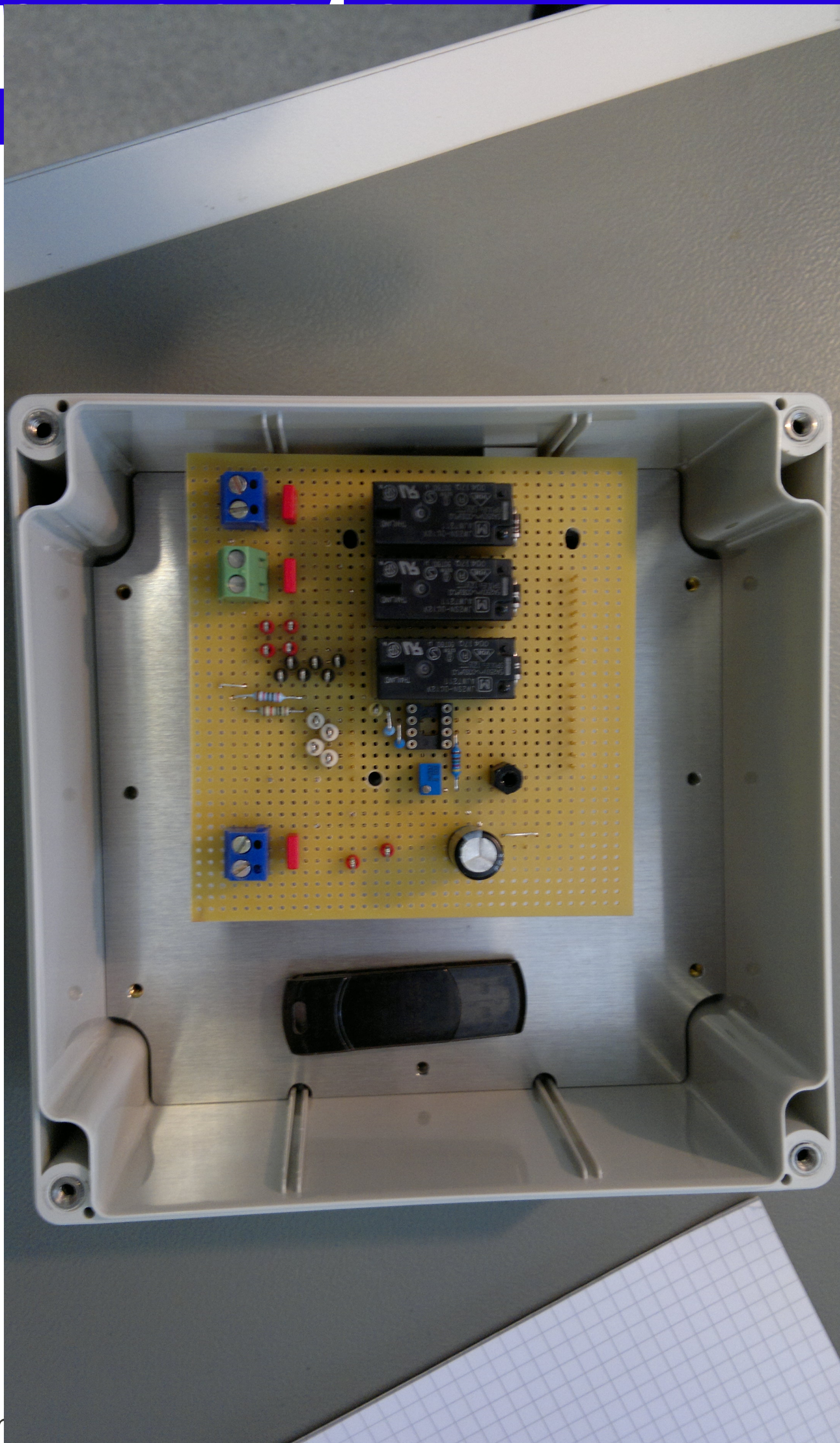
Status & current activities



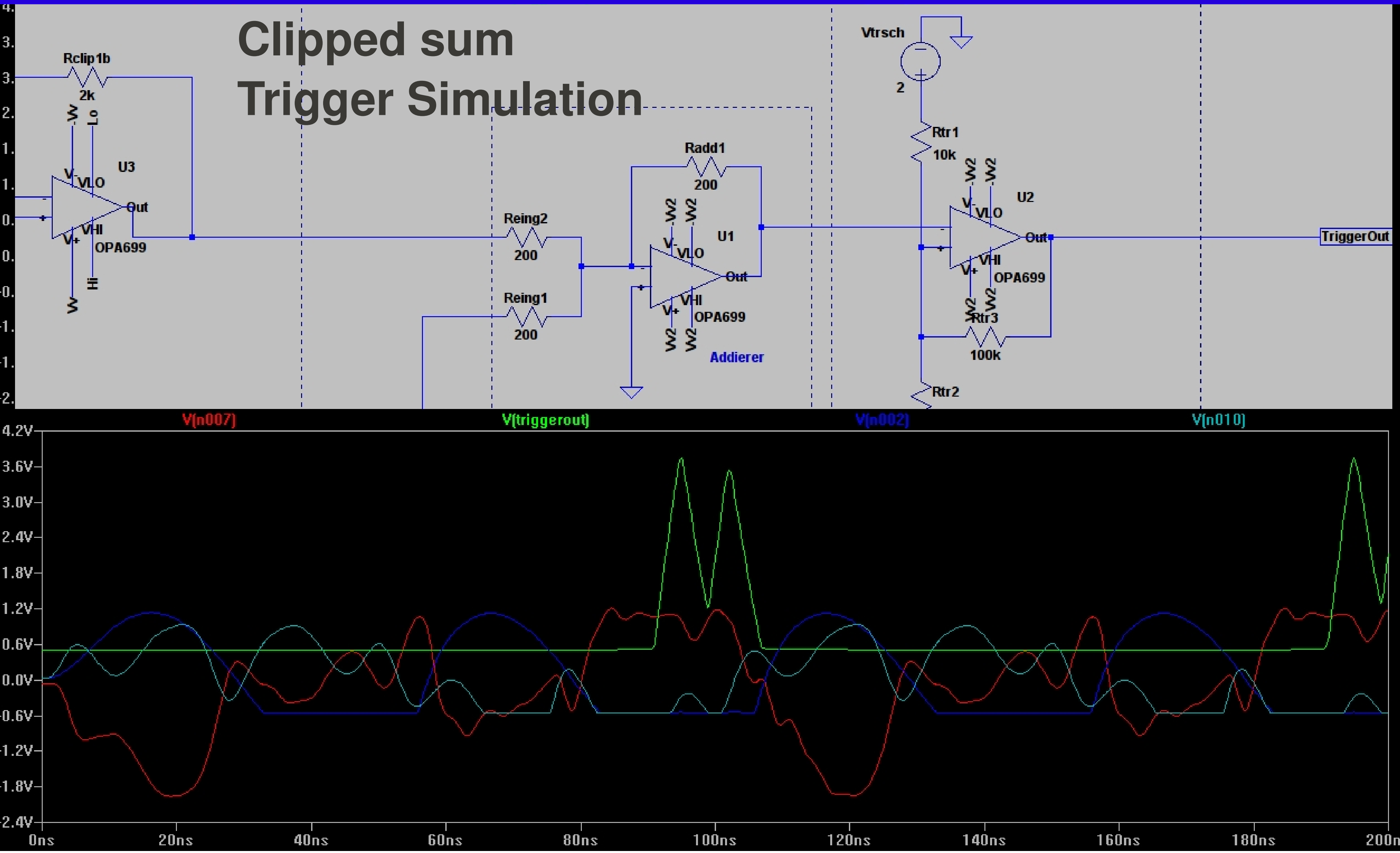


Available comp





Available components



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

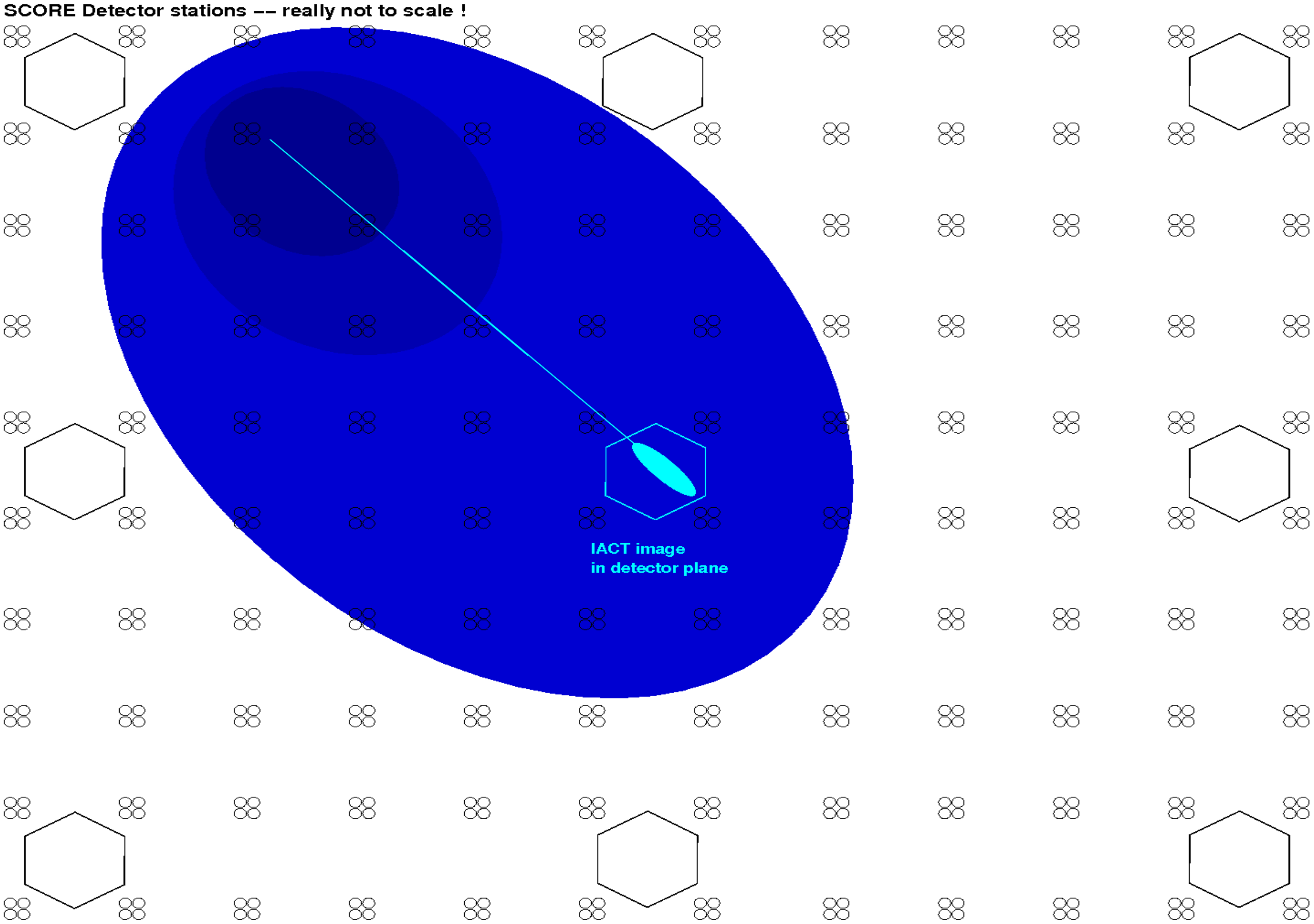
HiSCORE prototype at TUNKA

- 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

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 km^2 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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[3] K. Bernlöhr (2008), astrop-ph preprint, arXiv:0808.2253

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[5] M. Tluczykont, T. Kneiske, D. Hampf & D. Horns (2009), Proc. of the ICRC 2009, arXiv e-print (arXiv:0909.0445v1)

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[Shibata et al. 2010] M. Shibata, Y. Katayose, J. Huang and D. Chen, ApJ 716, 1076 (2010)

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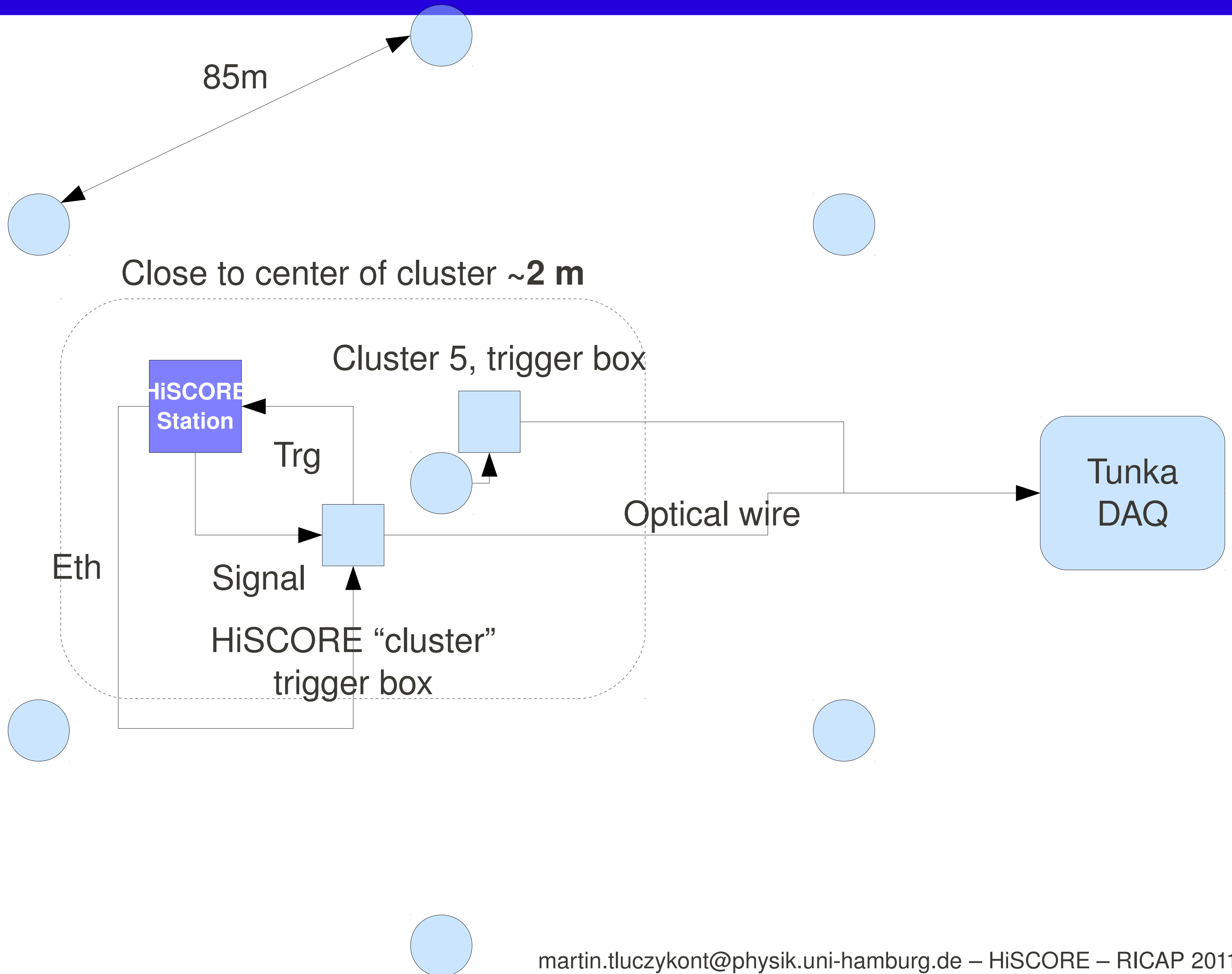
Backup

HiSCORE prototype at TUNKA

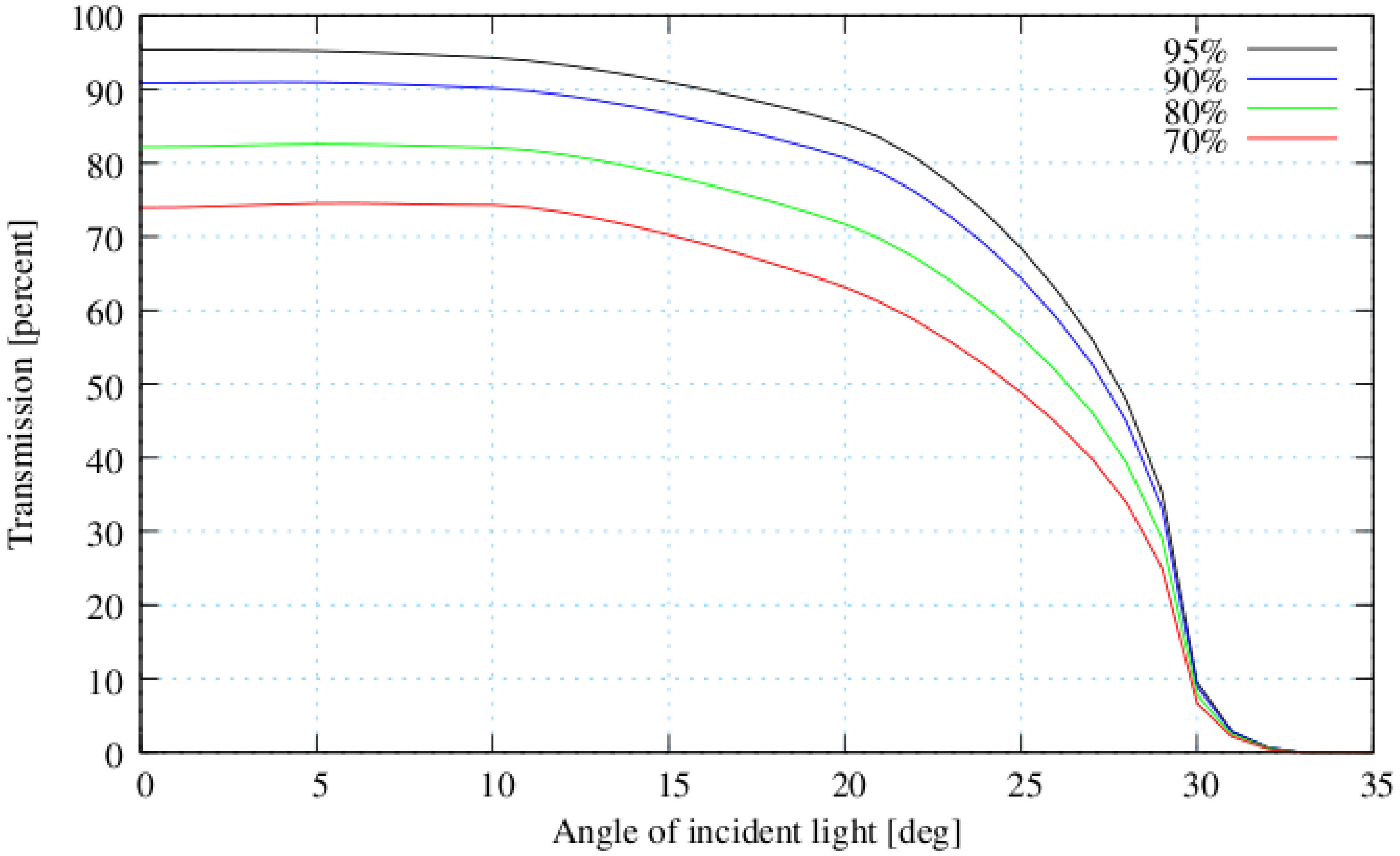


Expected night-sky background trigger rate

Separate NSB simulation, 4-channel station:

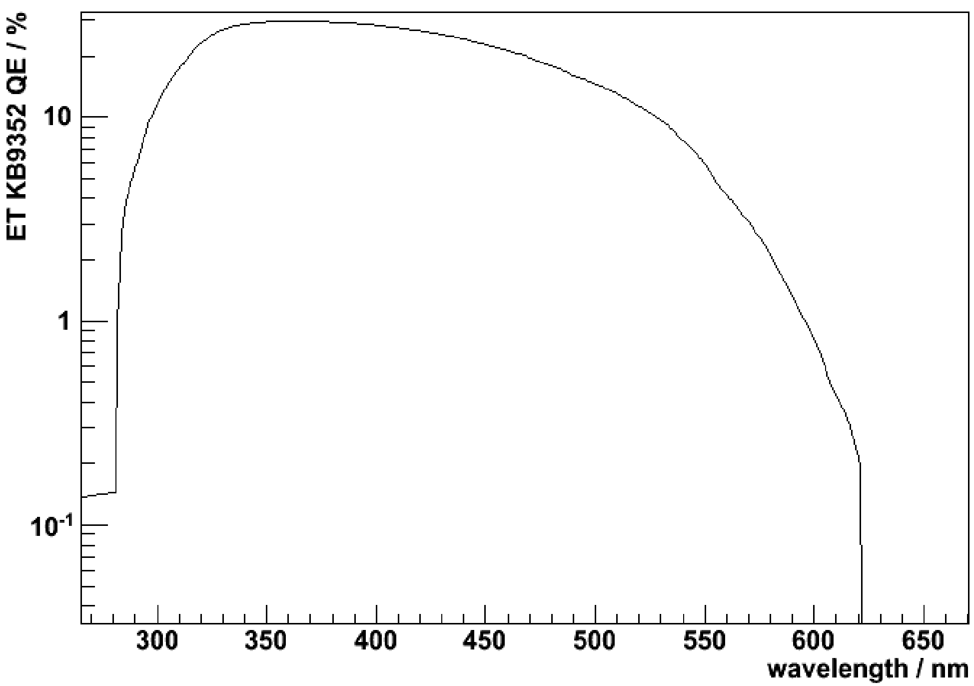
- NSB-rate from measurement in Australia [Hampf et al. 2010]
- Arrays of Photon times: equally distributed random numbers
- Pulse shaping + afterpulsing
- 4-channel coincidence trg:
  → channel-amplitude-clipping
  → analog sum of 4 clipped signals
  → discriminate sum
- Resulting **noise file:** 2s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

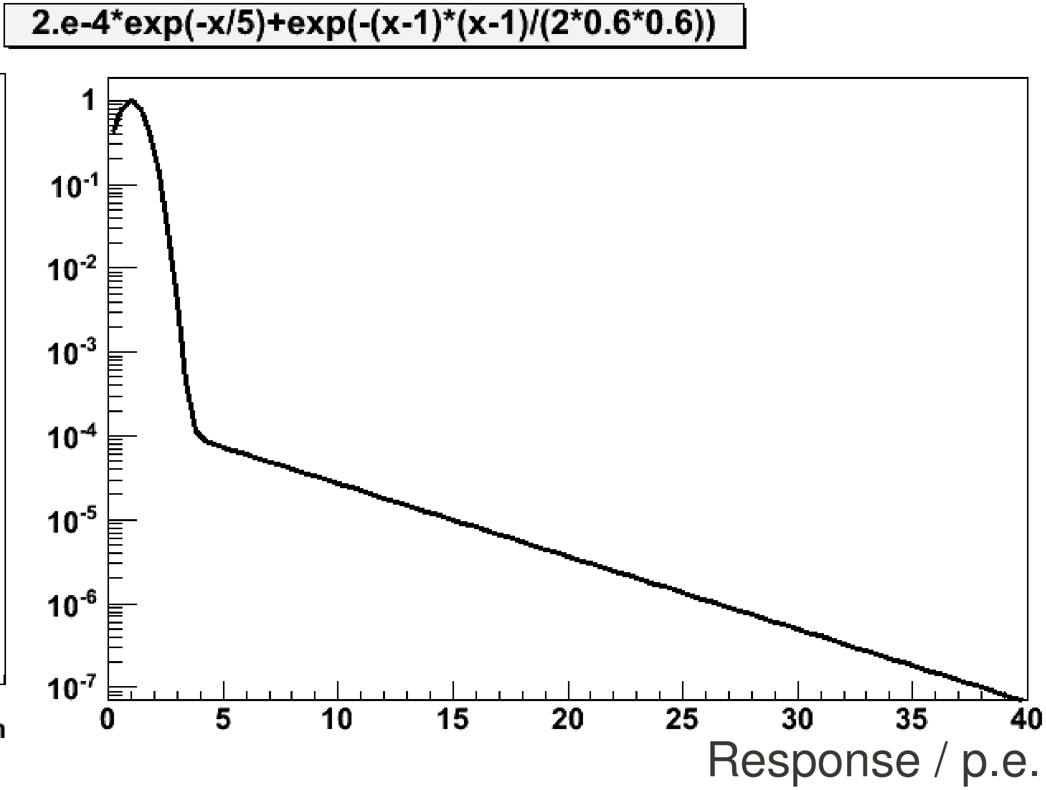
Winston cone acceptance



PMT simulation

- Wavelength-dependent QE simulated
- Photomultiplier response including afterpulses





Direction reconstruction

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

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

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

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

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

Shower height in km

Slope of atmospheric refractive index

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

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Zenith angle

Direction reconstruction

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

Slope of atmospheric refractive index

r: Distance from shower core to detector

Shower height in km

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

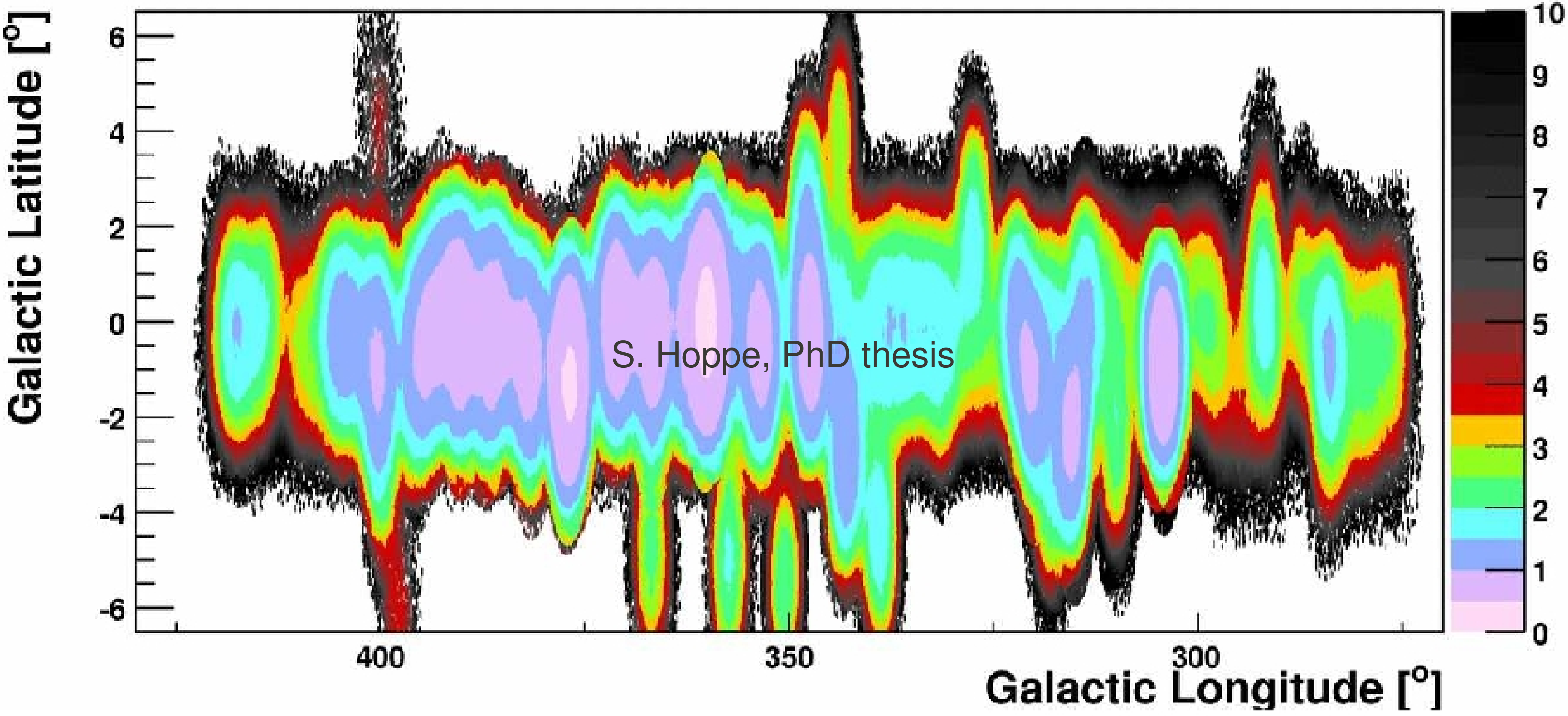
$$k(r,z) = r^2 + z^2\,\frac{1}{\cos(\theta)^2} + 2\,r\,z\,\tan(\theta)\,\cos(\delta)$$

Zenith angle

Free parameters: height & direction

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

H.E.S.S. survey sensitivity



Expected pevatron signal

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

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

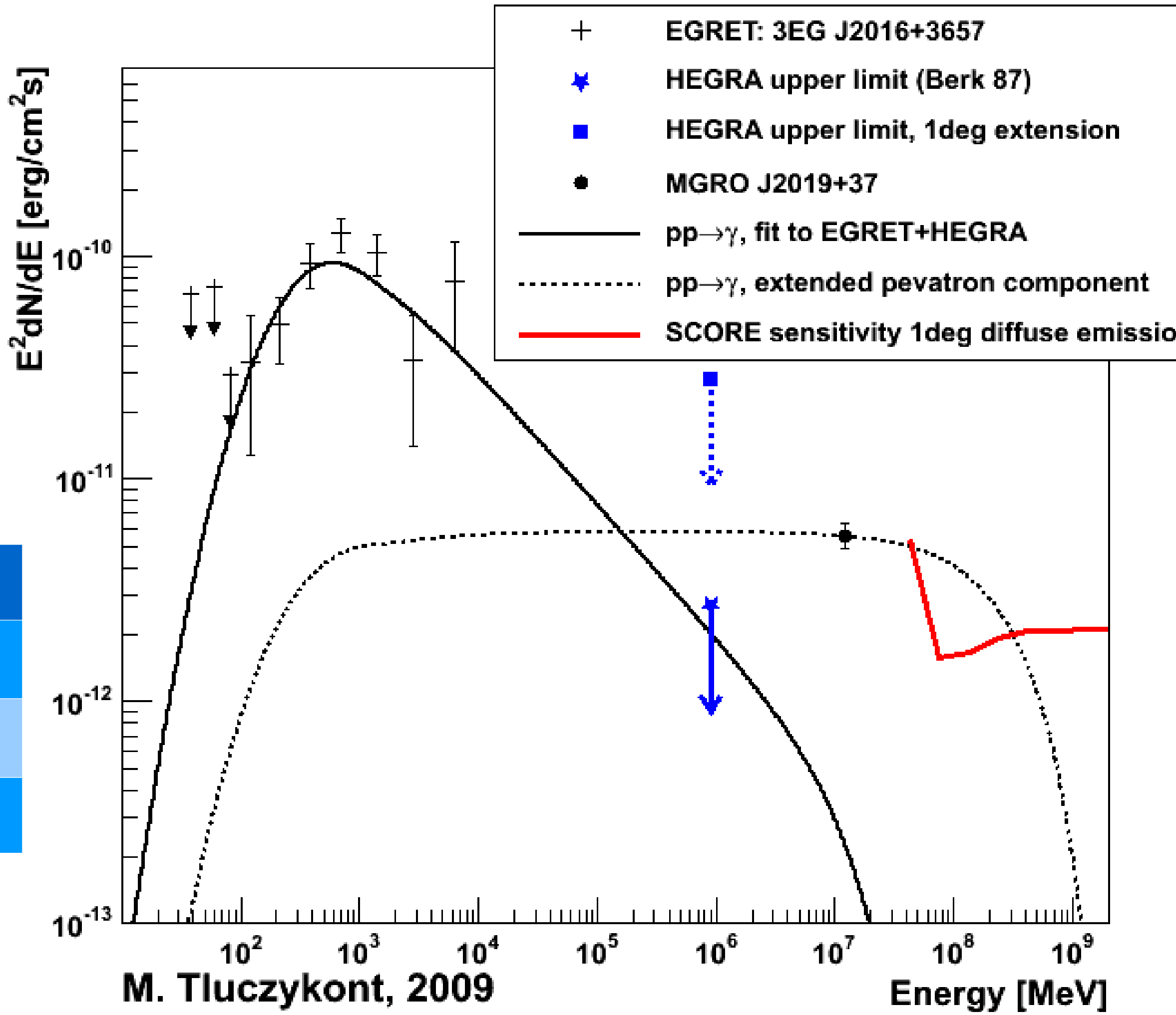
Fold dN/dE and Hörandel
w/ post-reconstruction area

Integral event numbers

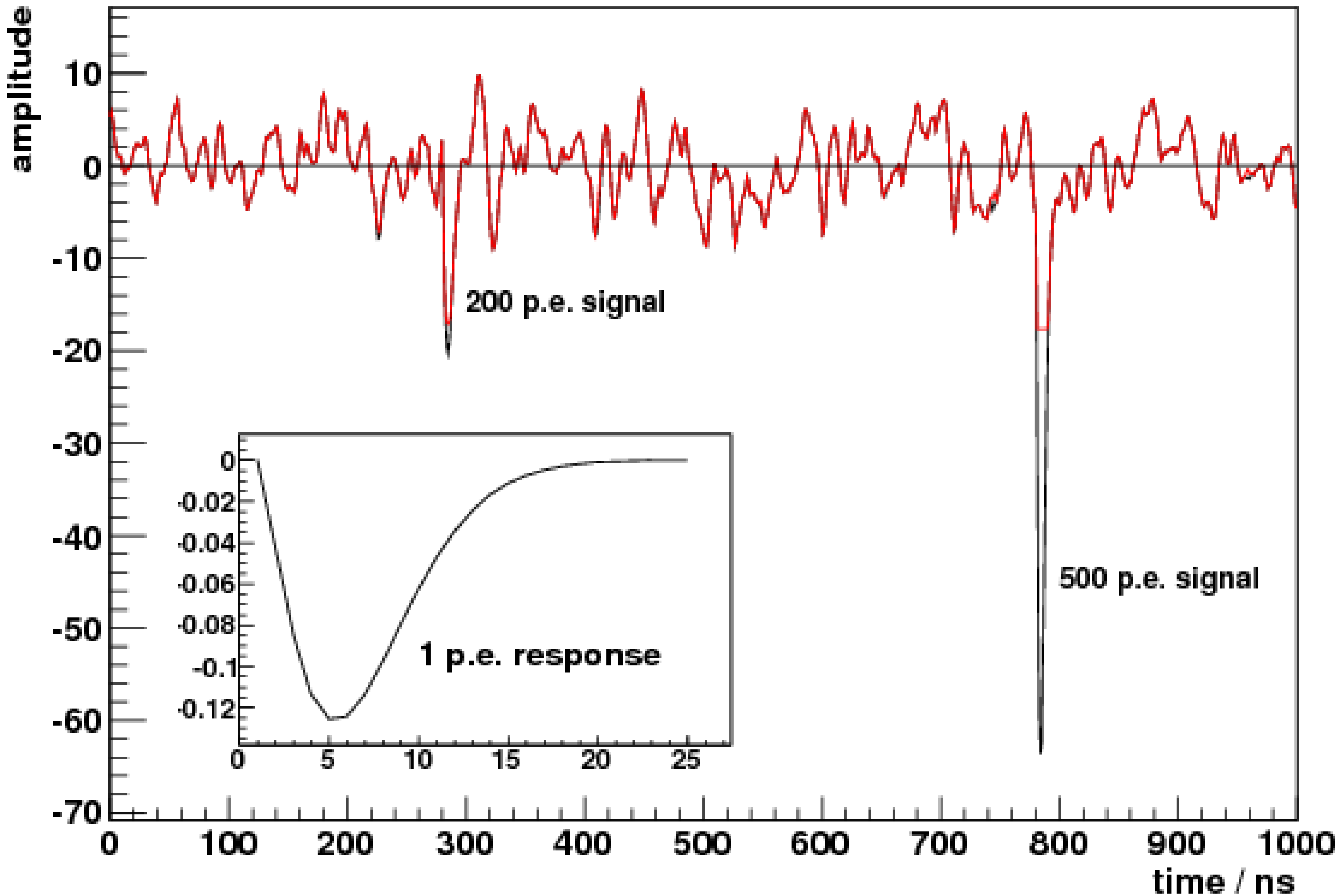
2deg source region

5 years observation time

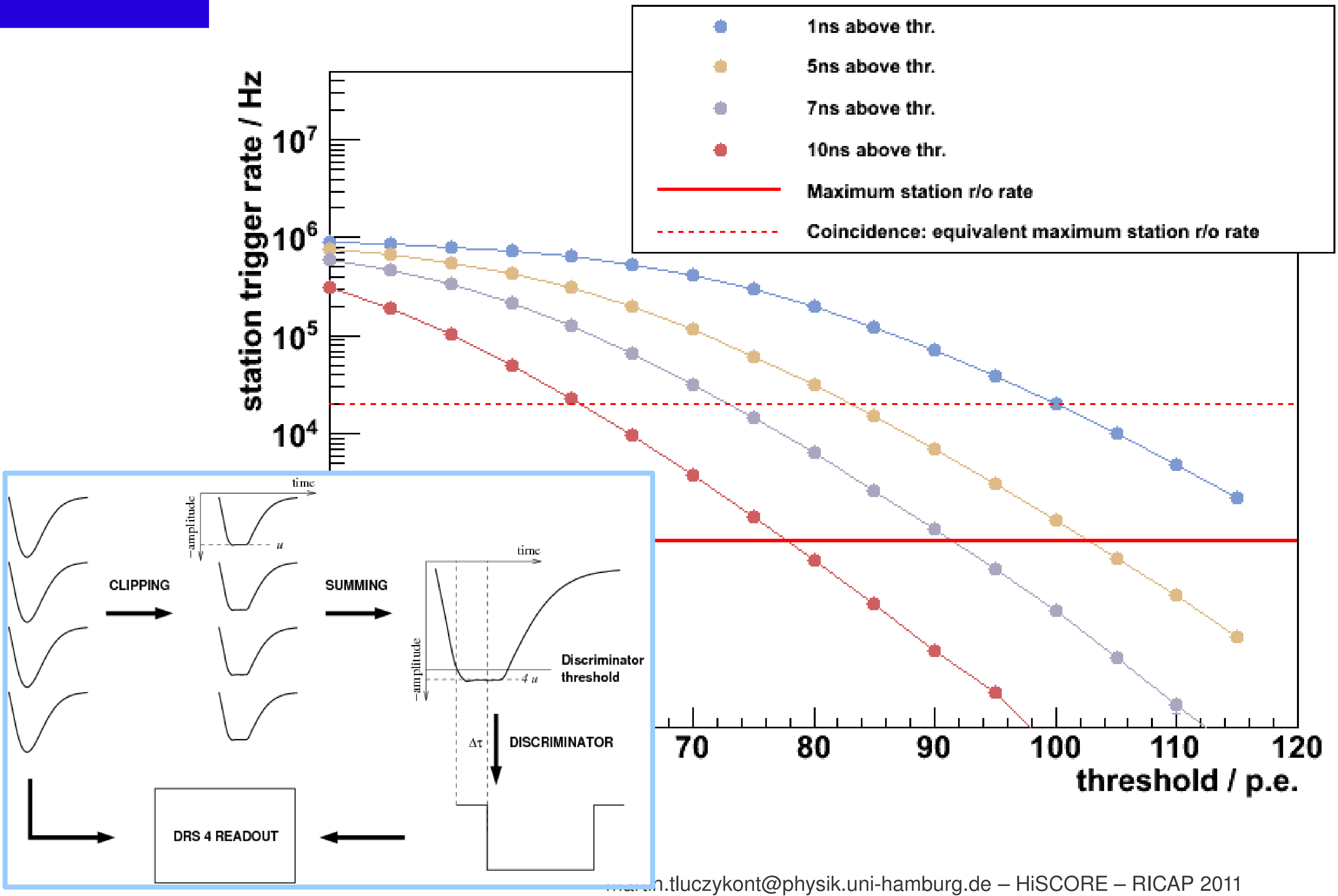
Energy	gammas	hadrons	Signific.
>50 TeV	7000	1050000	6.8
>100 TeV	4000	450000	5.9
>1PeV	100	20000	0.7



Signal and noise

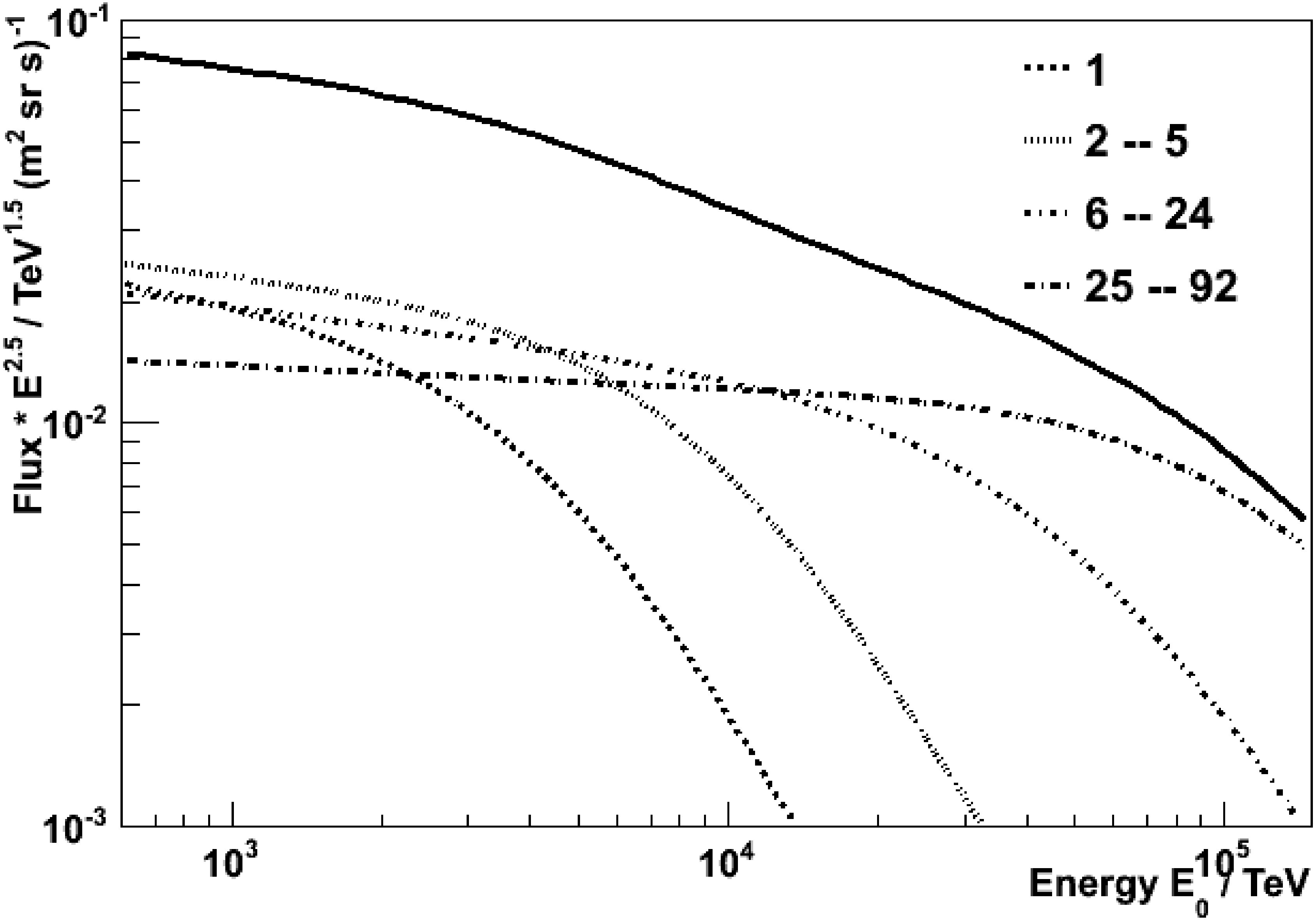


Expected night-sky background trigger rate



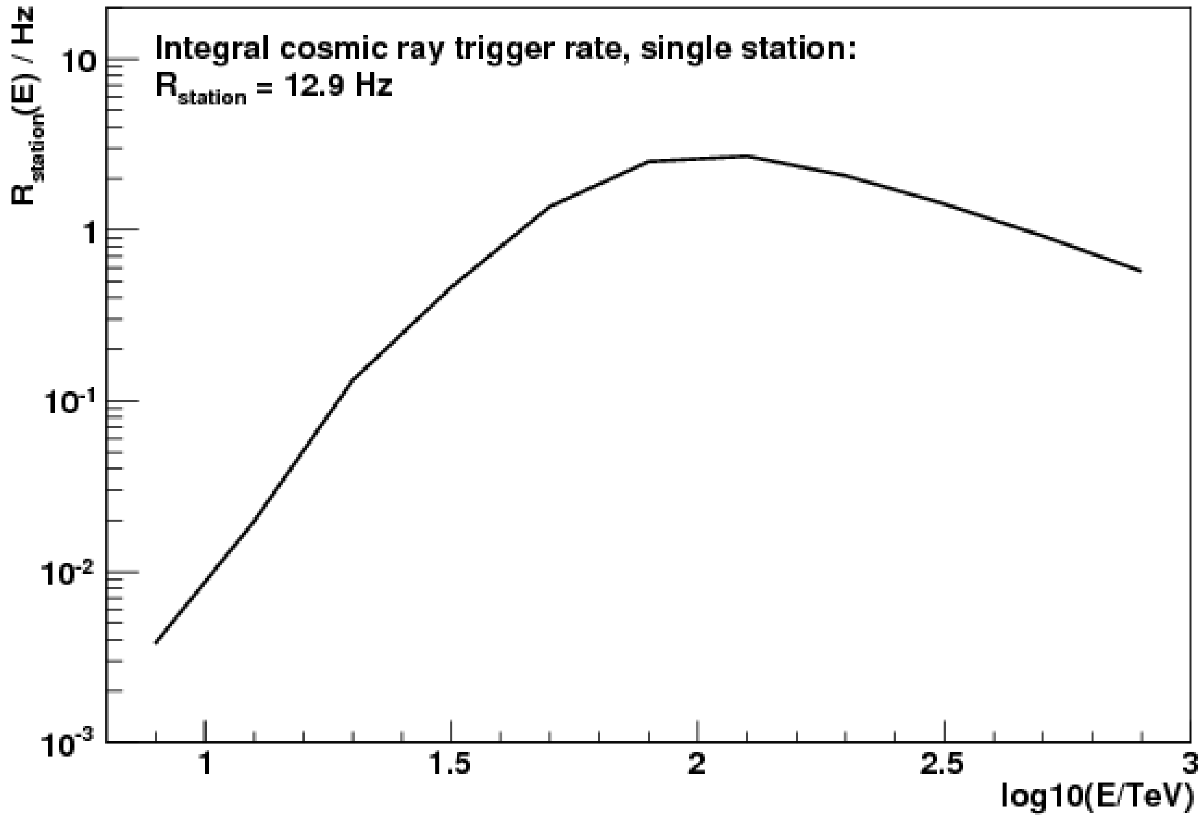
Hadron parametrization

Hoerandel 2003: polygonato model



Station hadron trigger rate

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



Array hadron trigger rates

Trigger rates for E > 10 TeV, before reconstruction cuts
Detector layout: simple grid, 10 km² (SCORE)
Trigger condition: single station trigger

Proton	774 Hz
He	436 Hz
N	257 Hz
Fe	90 Hz
Array rate, all particles	~ 2 kHz
Single station rate	~ 13 Hz
NSB per station	< 300 Hz

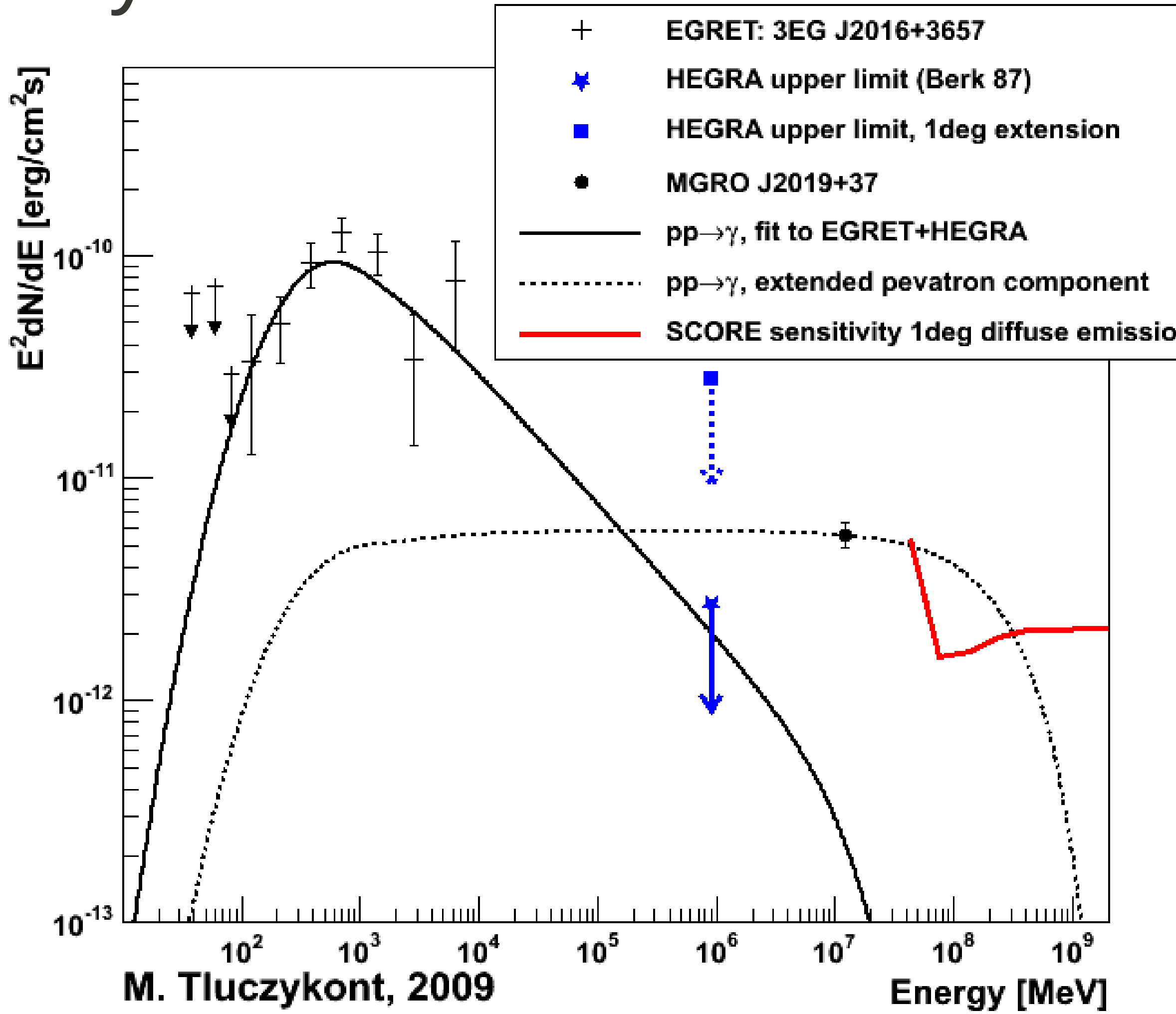
Pevatron emission from Cygnus ?

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



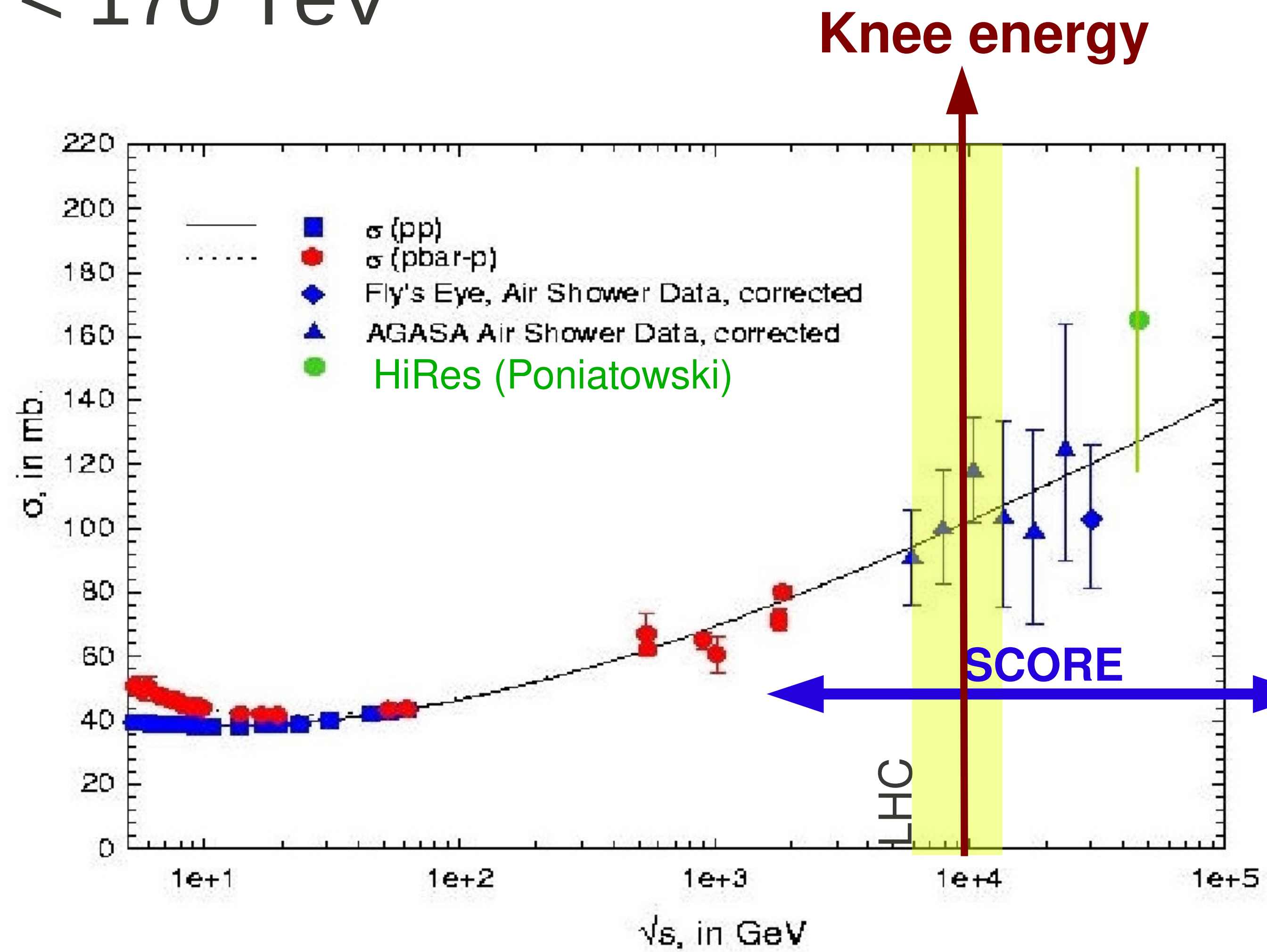
Milagro signal might be dominated by extended pevatron emission !

SCORE: resolve emission from 10 TeV – 1 PeV

p-p cross-section

Correlation shower depth / first interaction
→ measure interaction length in air **σ(p-p)**

SCORE: 1.7 < E_{CM} < 170 TeV



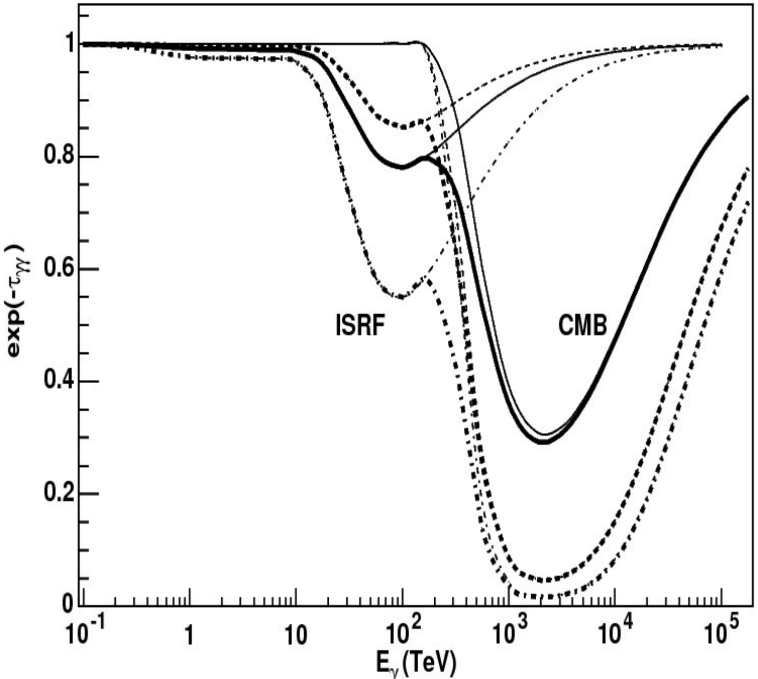
Particle physics-
origin of knee ?

Overlap:

LHC

CR experiments

Propagation: Galactic Absorption & CMB



Moskalenko et al. 2006

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

estimate ISRF density

CMB well known: **distance estimate?**

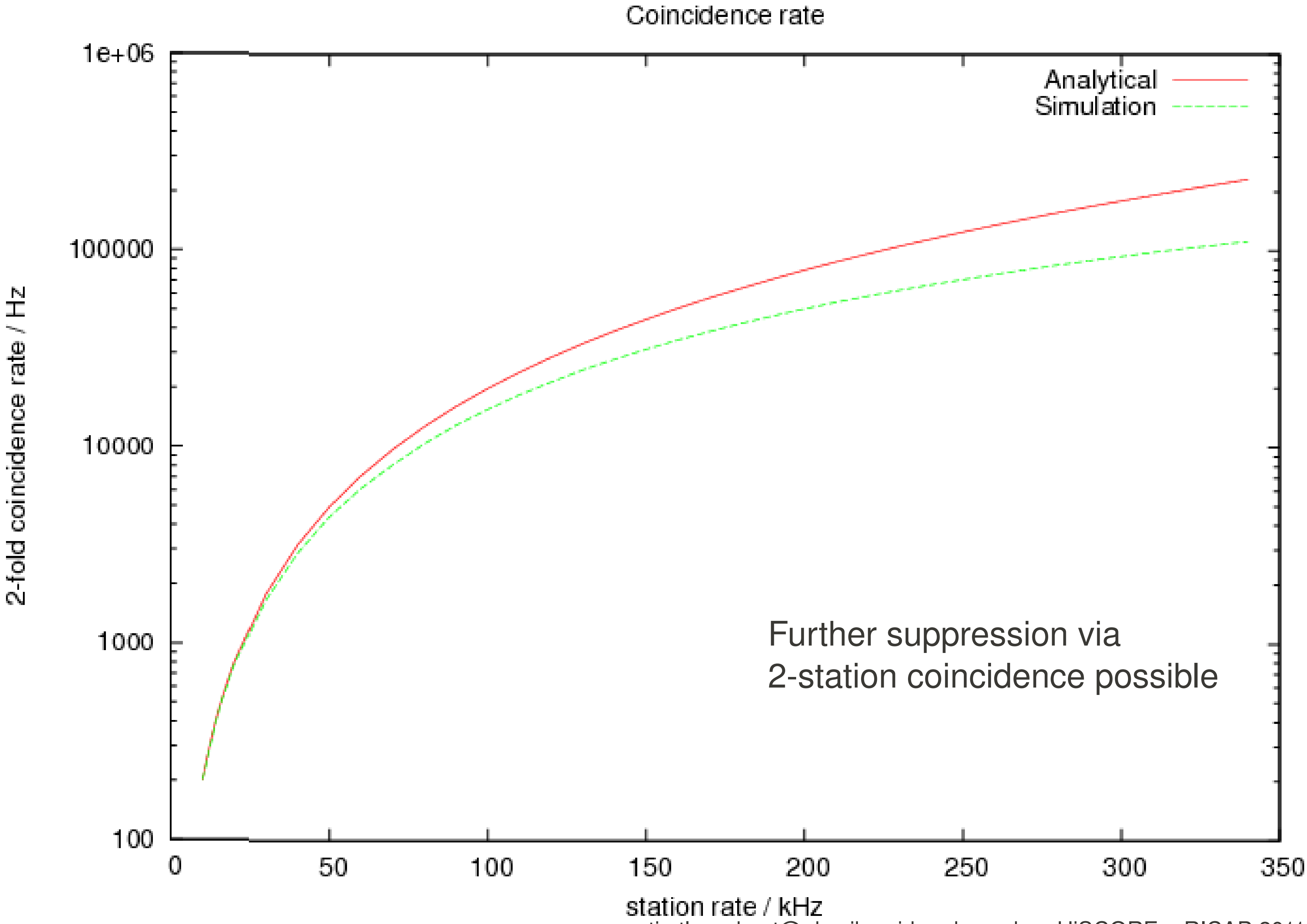
Weakening of absorption by:

Photon / axion conversion in Galactic Magnetic field

Photon / hidden photon oscillation

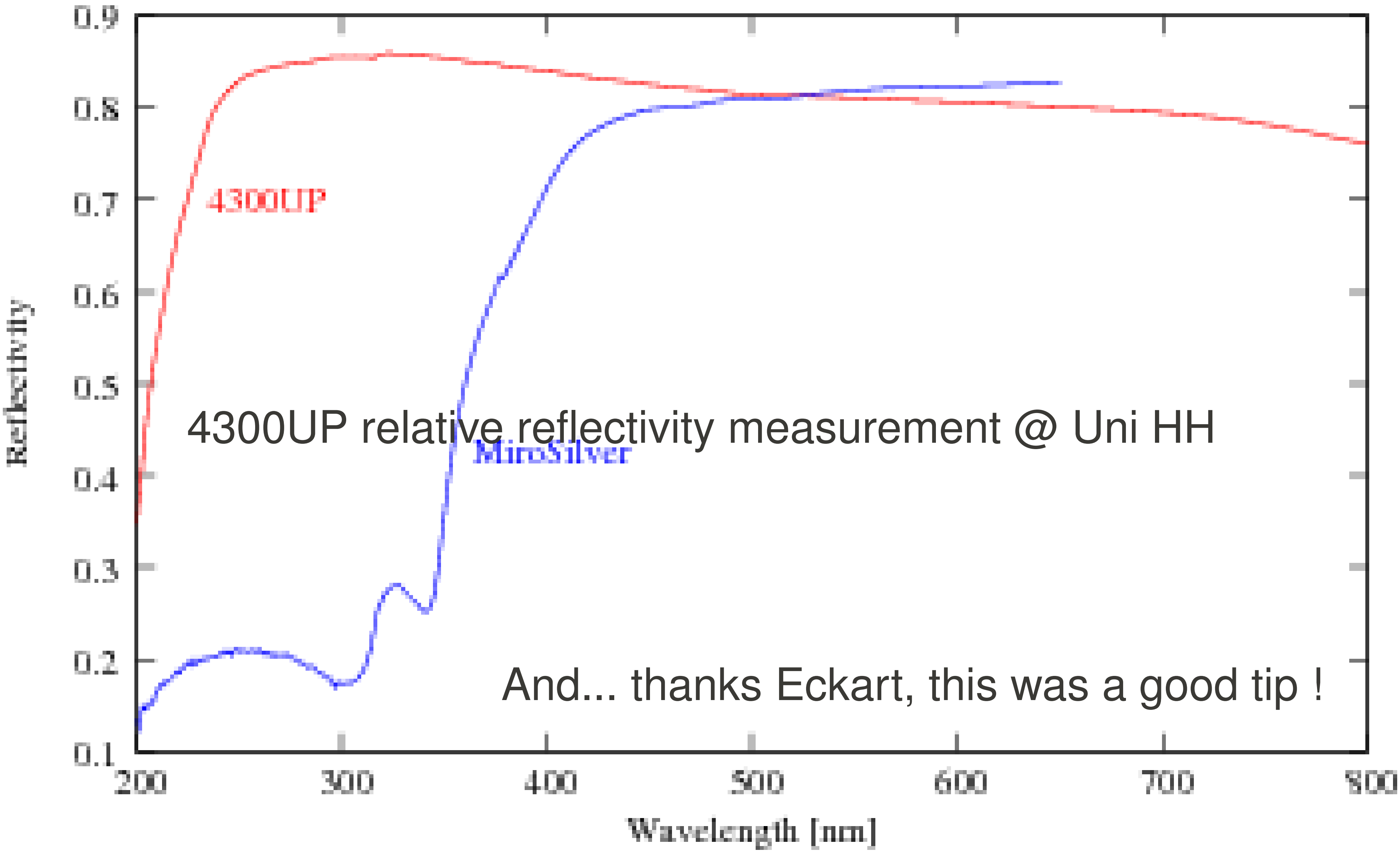
Lorentz invariance violation (modification of e^+e^- threshold)

Expected night-sky background trigger rate



Further suppression via
2-station coincidence possible

Hardware Prototyping / Testing



4300UP relative reflectivity measurement @ Uni HH

And... thanks Eckart, this was a good tip !

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