HiSCORE first results

Gamma-rays and Cosmic rays

www.http://taiga-experiment.info/

Martin Tluczykont for the TAIGA Collaboration

RICAP 2016, Frascati, Roma

HiSCORE ⊂ TAIGA

TAIGA collaboration

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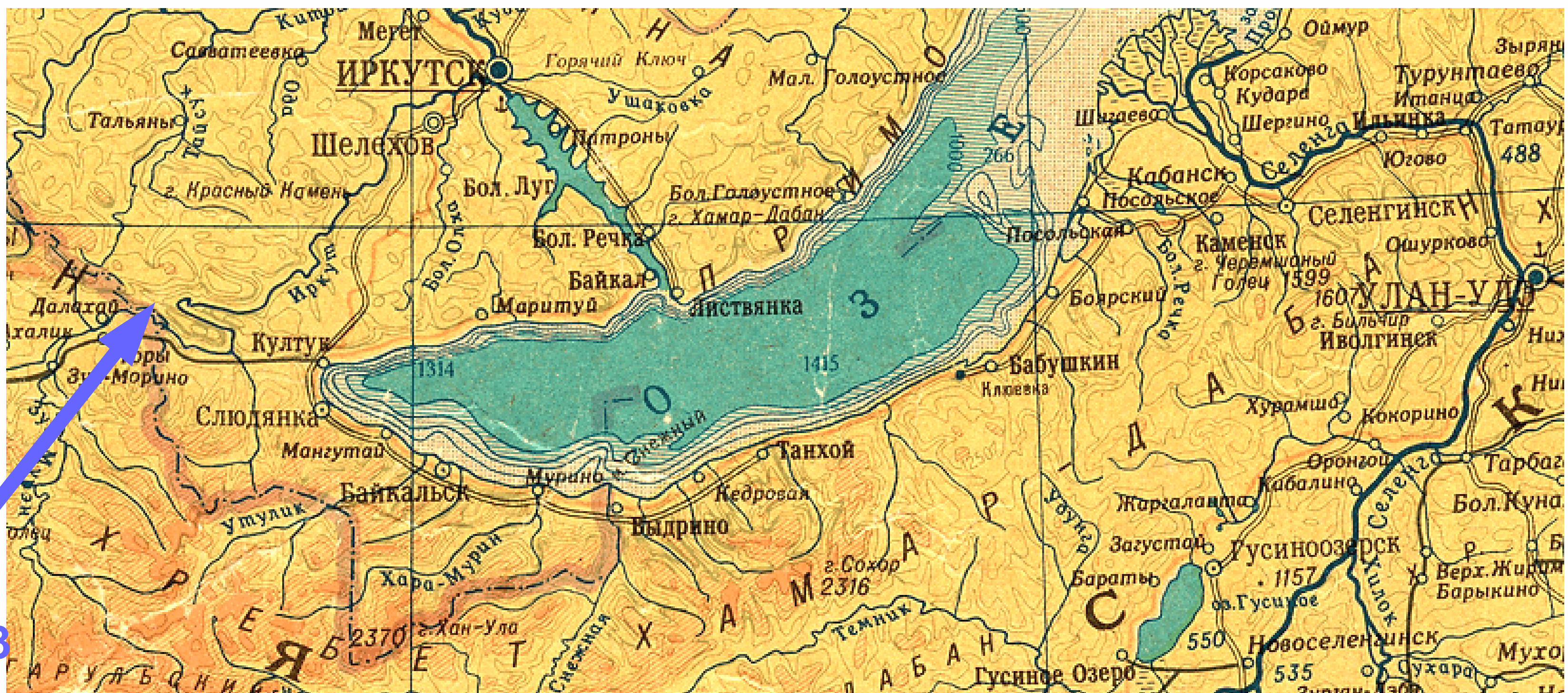
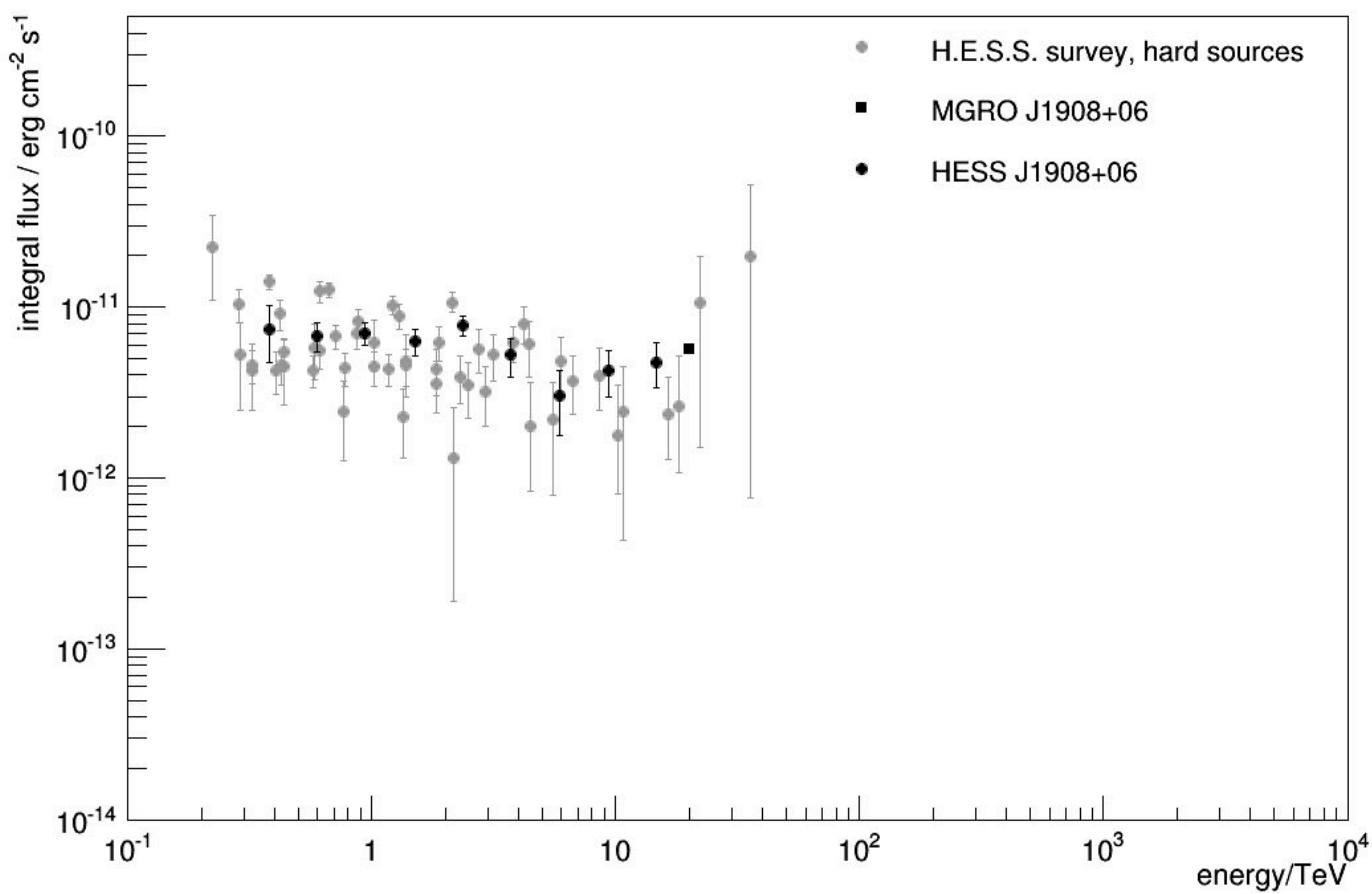
[2] Institute of Applied Physics, ISU, Irkutsk, Russia
[3] Institute for Nuclear Research of RAN, Moscow, Russia
[4] Dipartimento di Fisica Generale Universiteta di Torino and INFN, Torino, Italy
[5] Max-Planck-Institute for Physics, Munich, Germany
[6] Institut für Experimentalphysik, University of Hamburg, Germany
[7] IZMIRAN, Moscow Region, Russia
[8] DESY, Zeuthen, Germany
[9] NRNU MEPhI, Moscow,Russia
[10] JINR, Dubna, Russia



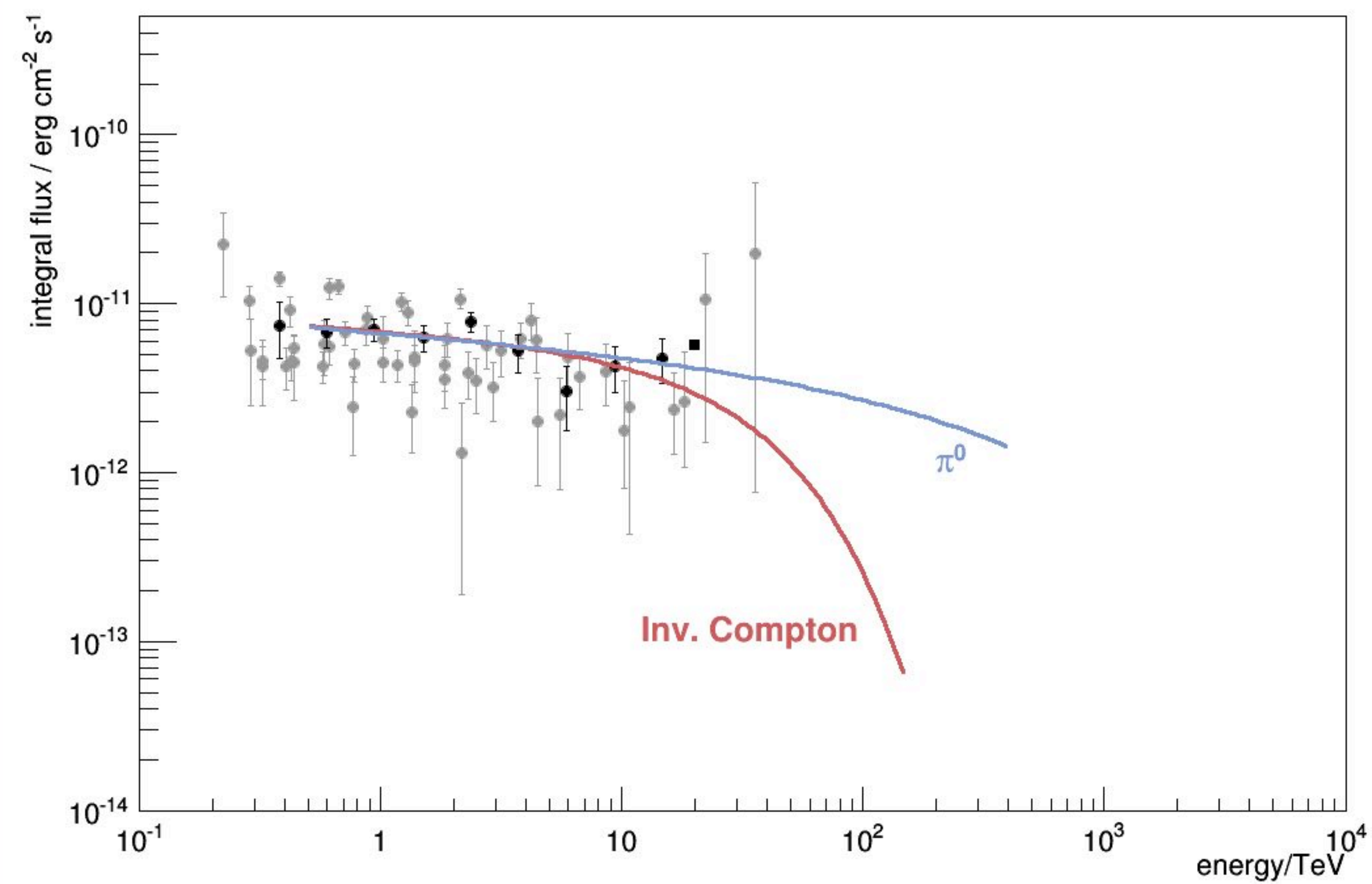
Tunka-133 site

Physics motivation

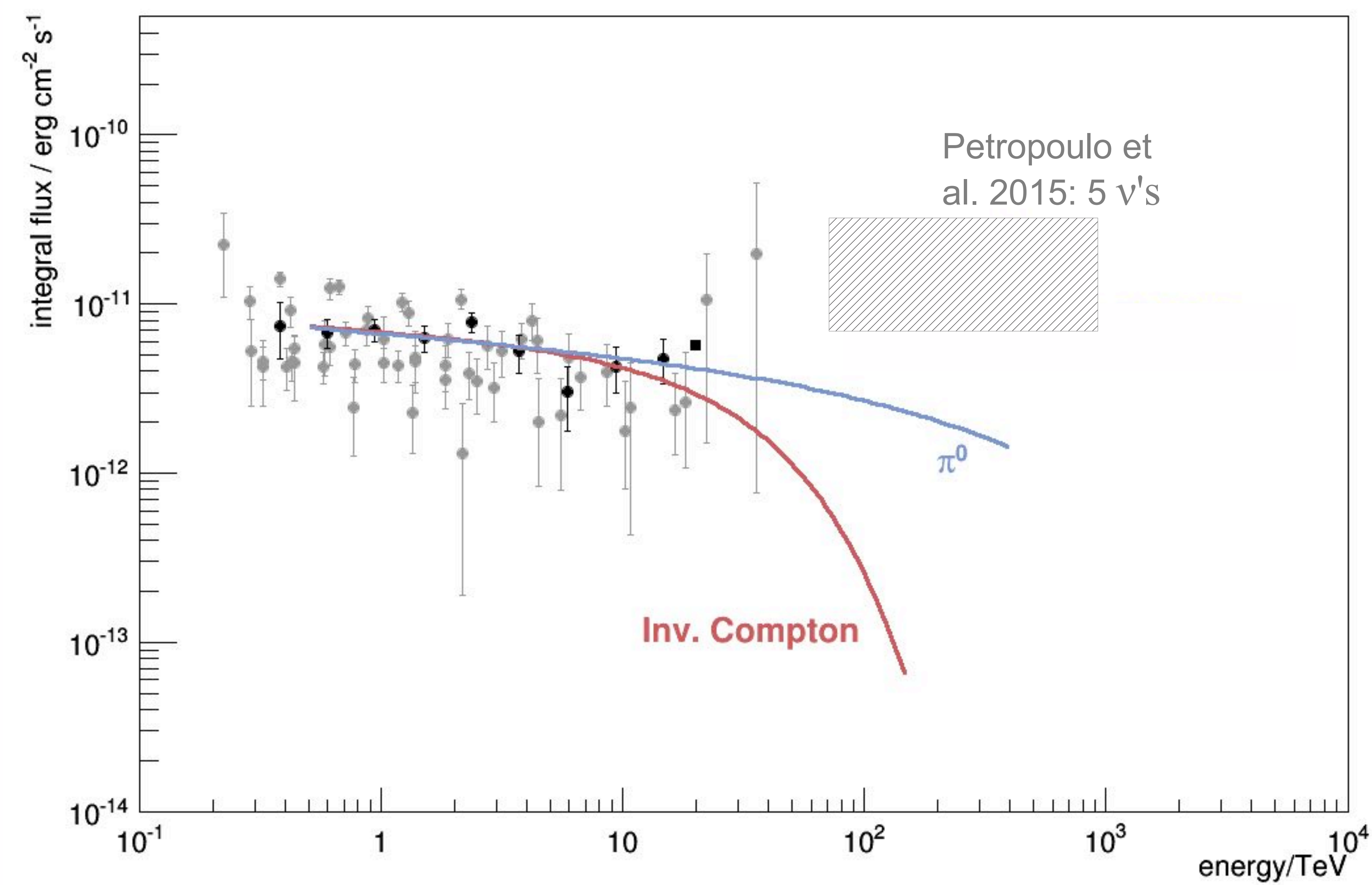
VHE-UHE Gamma-ray astronomy



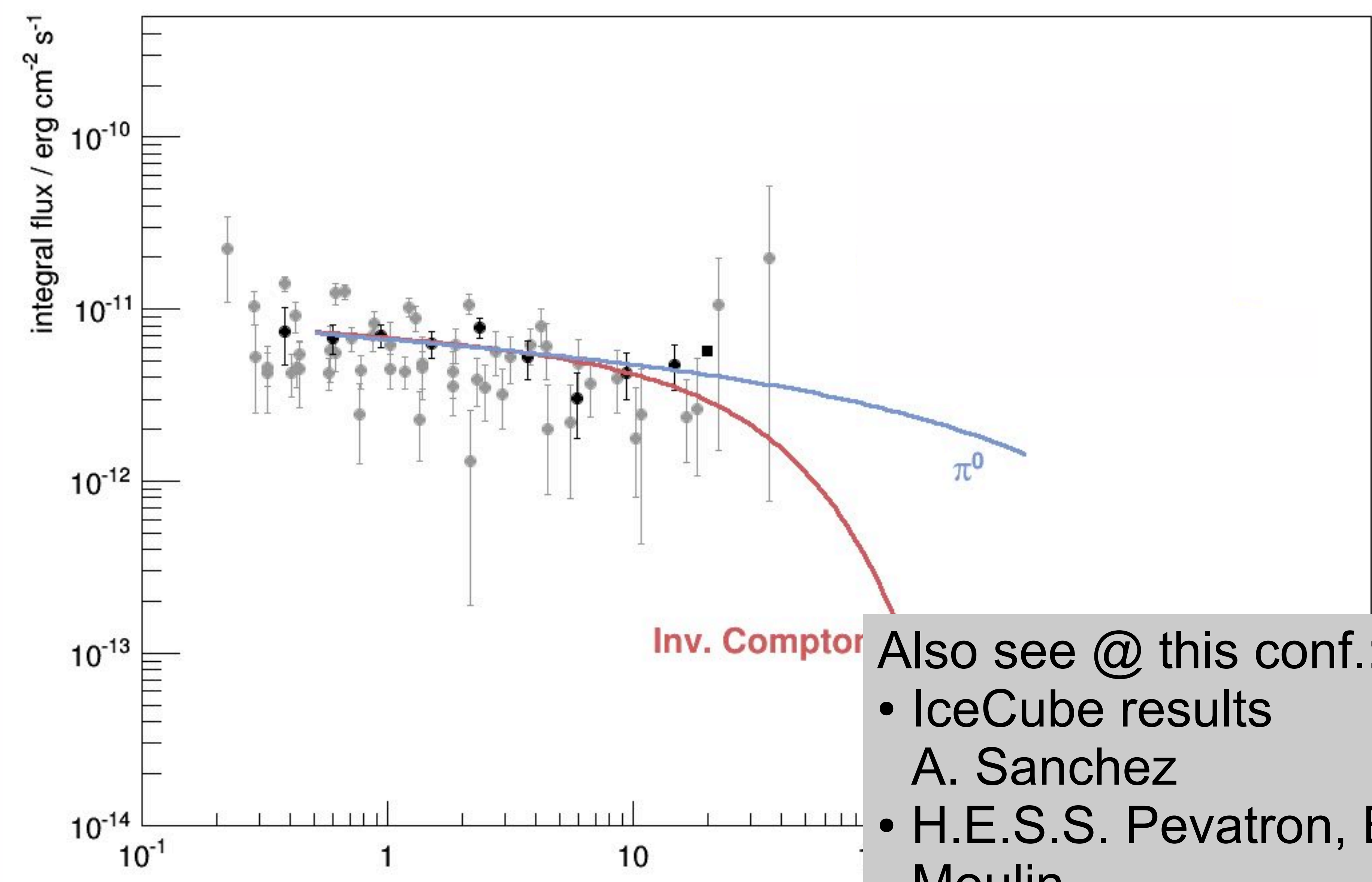
VHE-UHE Gamma-ray astronomy



VHE-UHE Gamma-ray astronomy



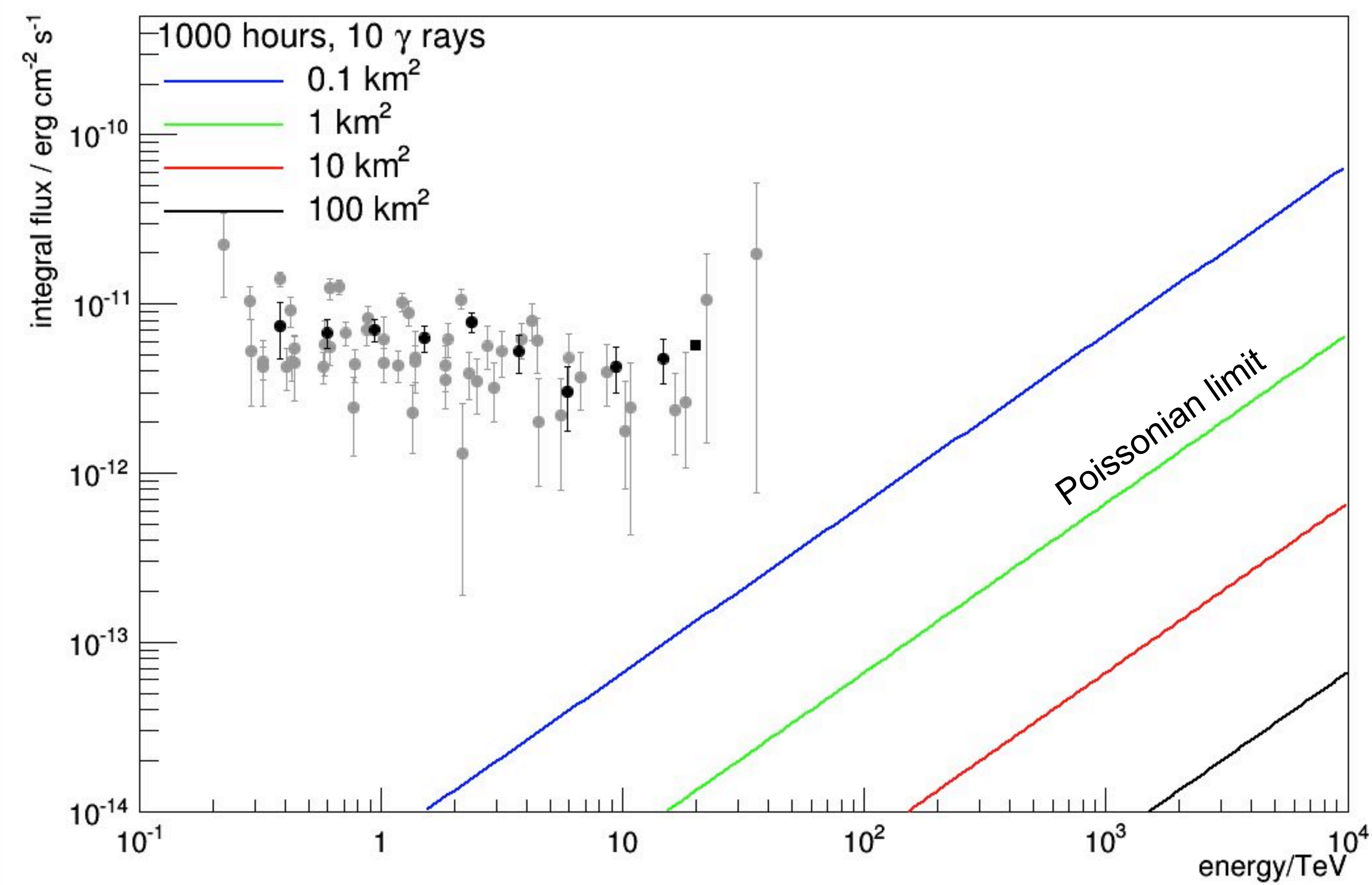
VHE-UHE Gamma-ray astronomy



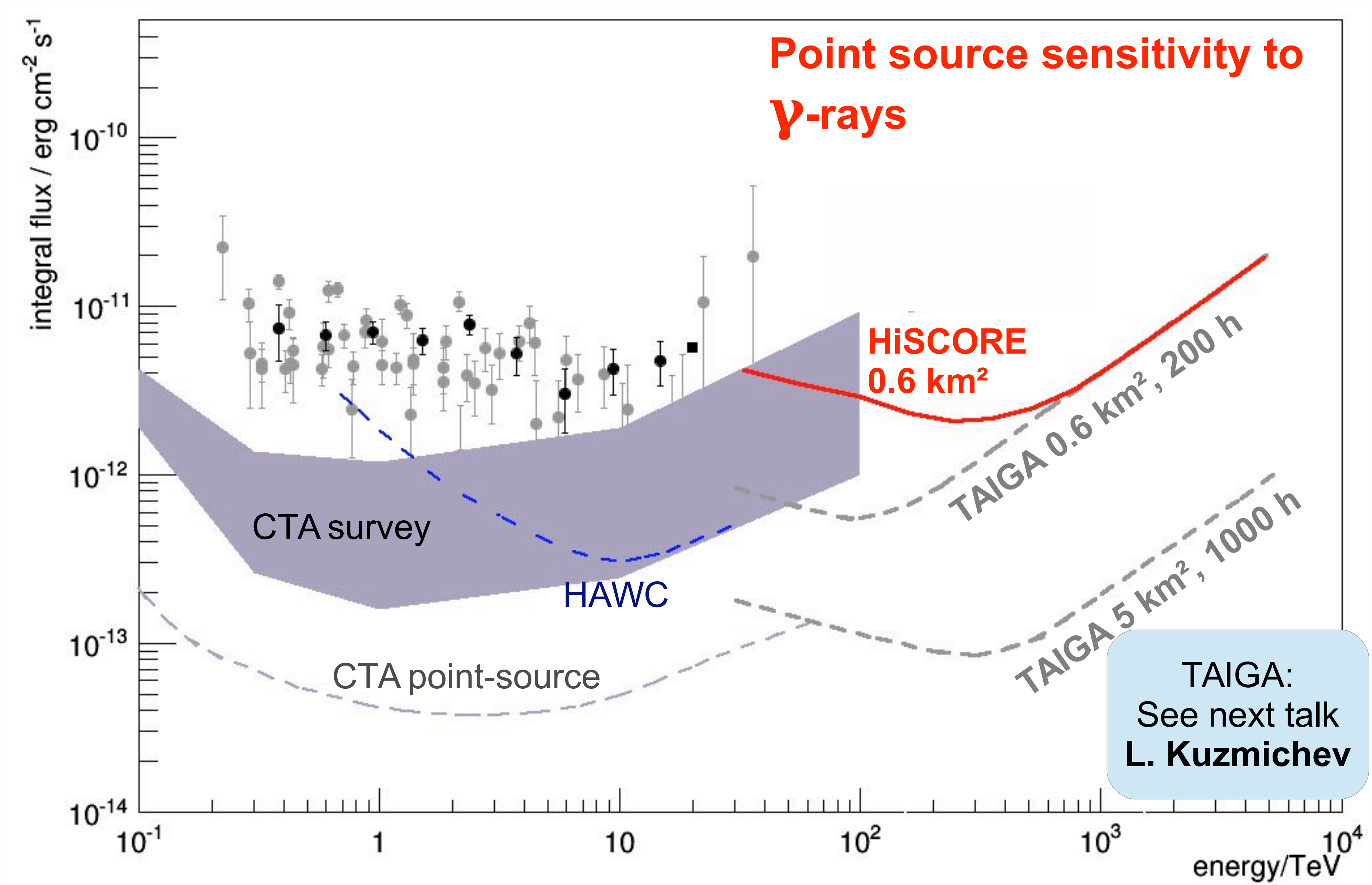
Also see @ this conf.:

- IceCube results A. Sanchez
- H.E.S.S. Pevatron, E. Moulin

Key to Multi-TeV-PeV: Area



VHE-UHE Gamma-ray Astronomy



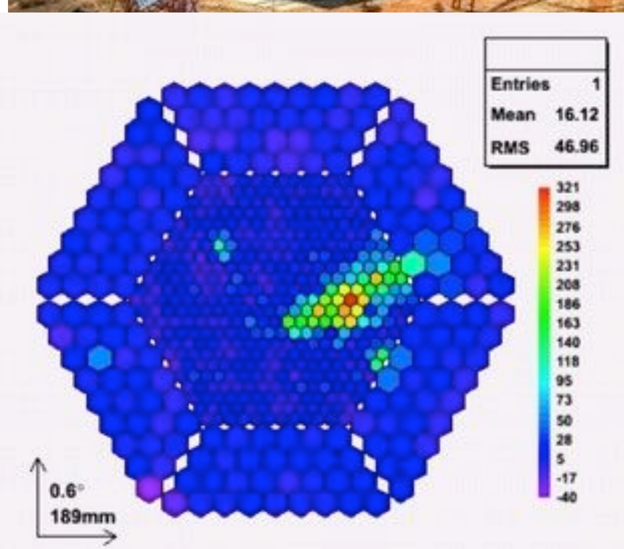
HiSCORE timing array
High Sensitivity Cosmic ORigin Explorer

(TAIGA: HiSCORE timing array + IACTs)

Detection method

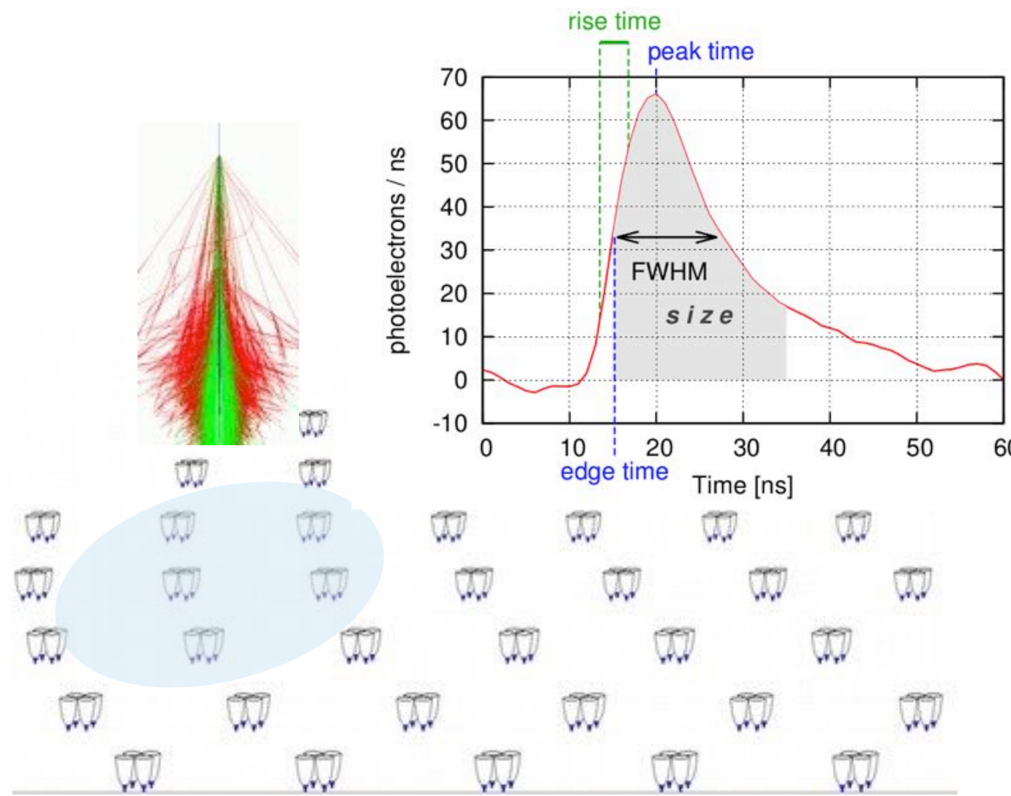
Air Cherenkov imaging and timing

Imaging arrays



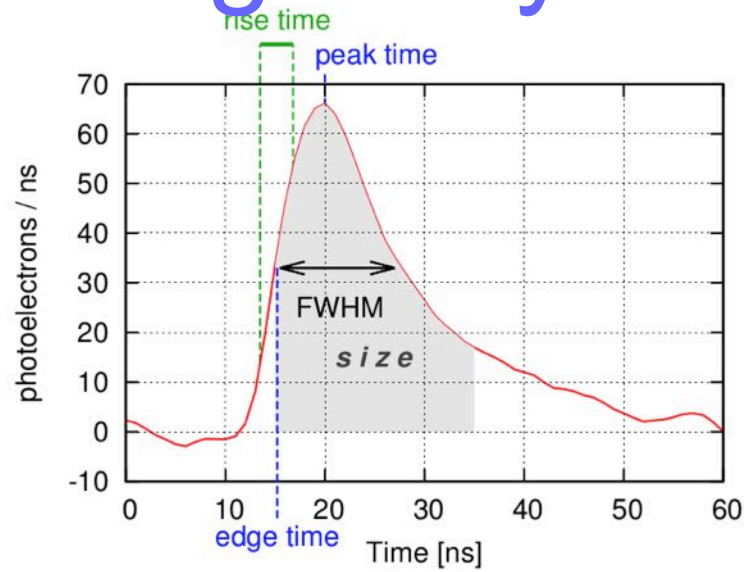
MAGIC camera image

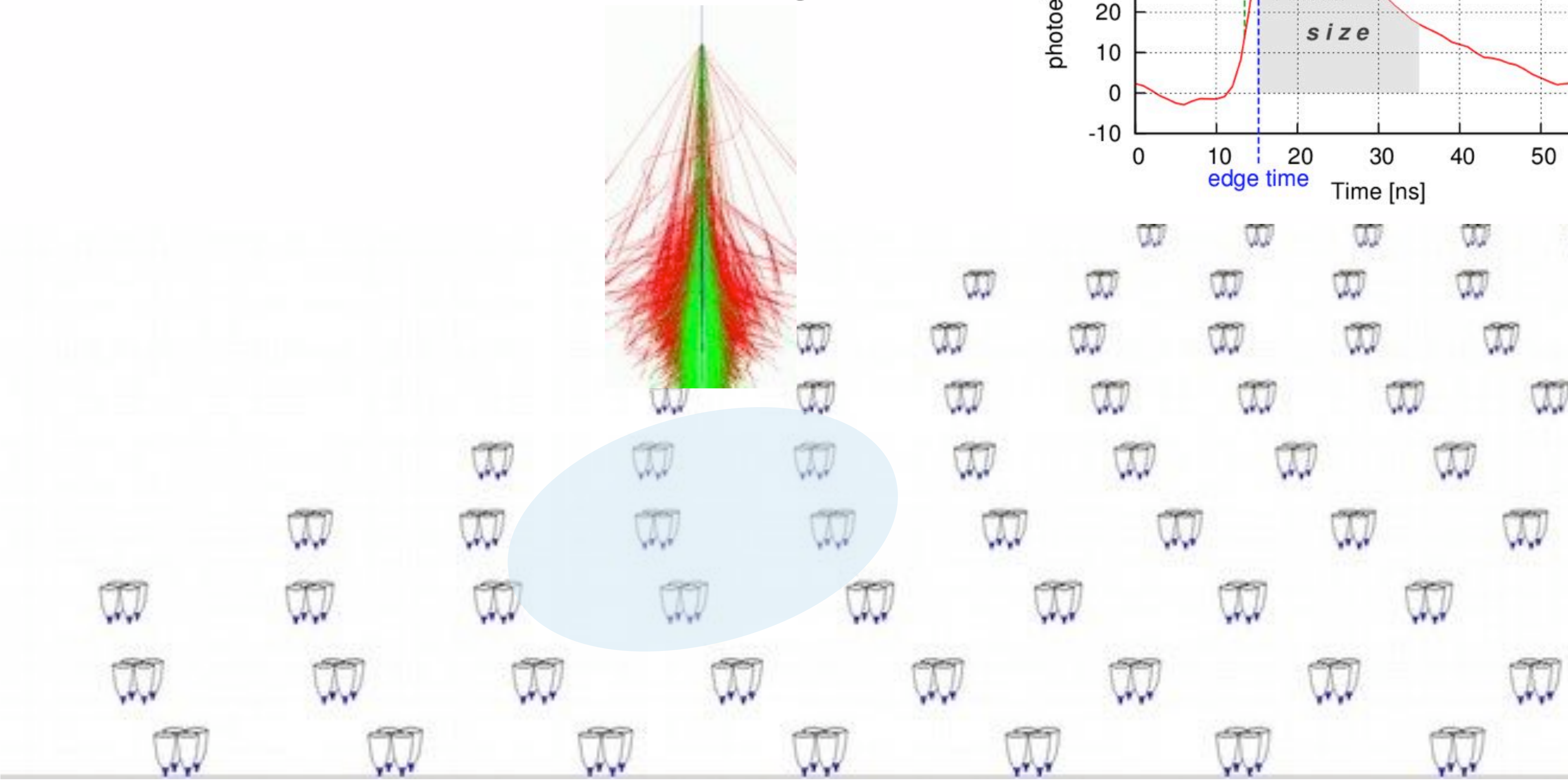
Timing arrays (non-imaging)



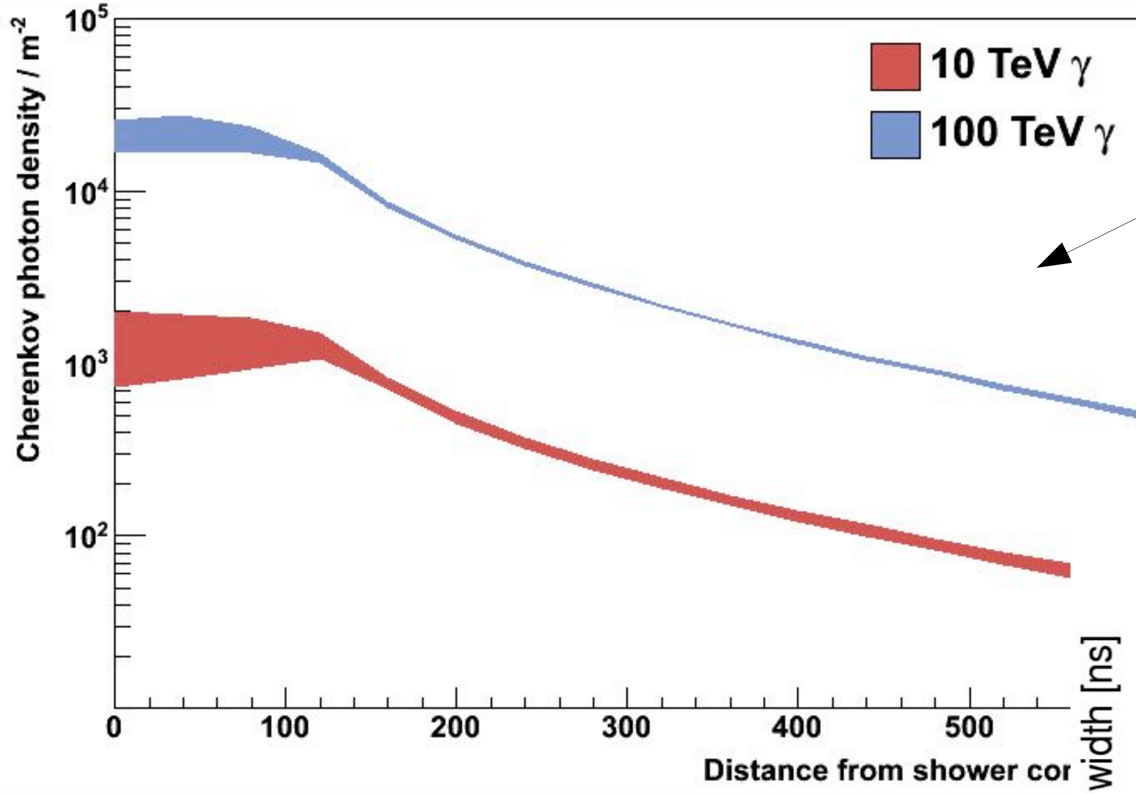
HiSCORE = TAIGA timing array

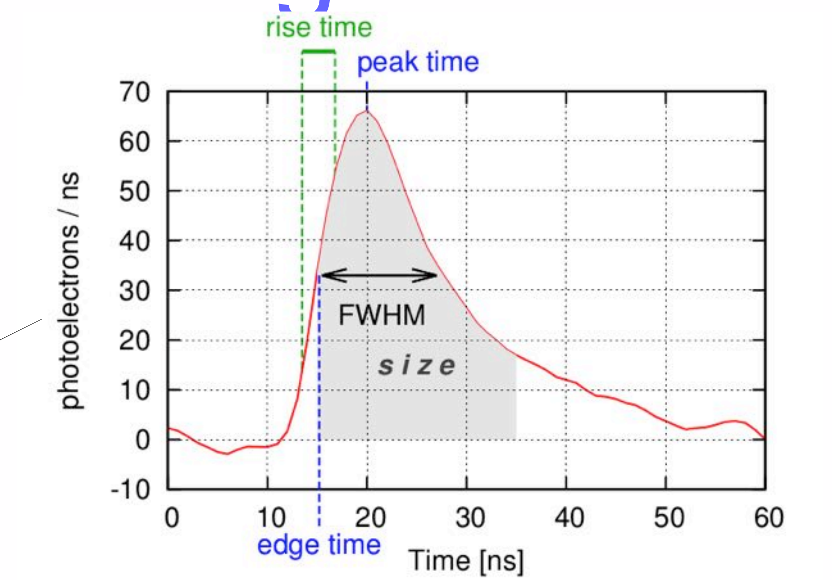
- Cherenkov light
  Shower front sampling

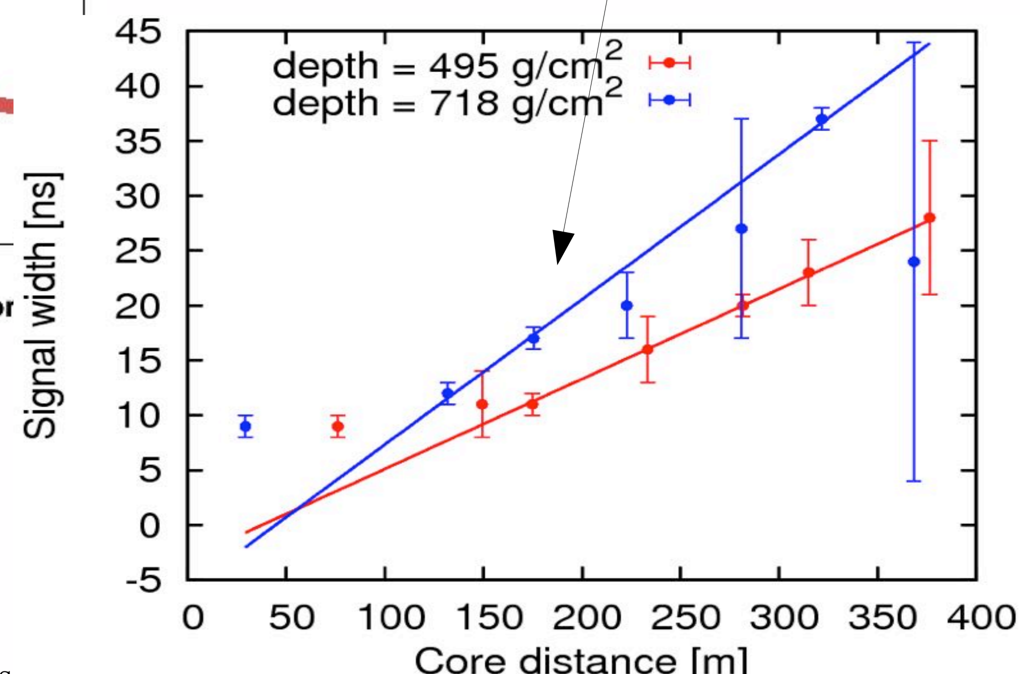




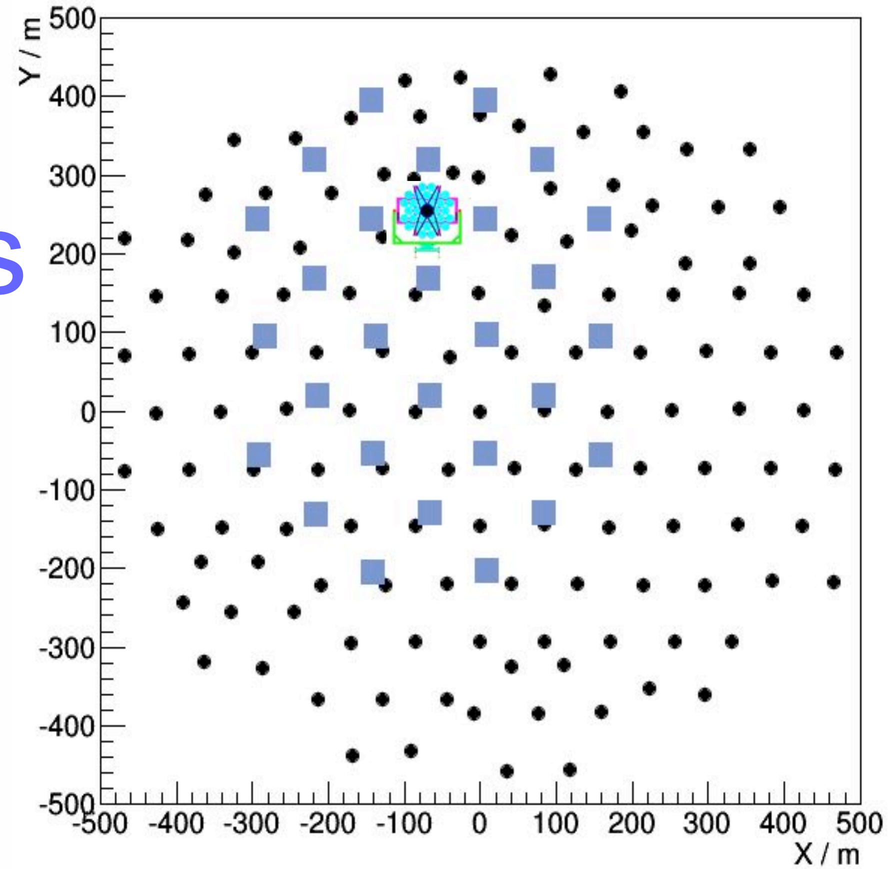
Air Cherenkov timing







HiSCORE = TAIGA timing stations



HiSCORE timing stations
Tunka 133 stations

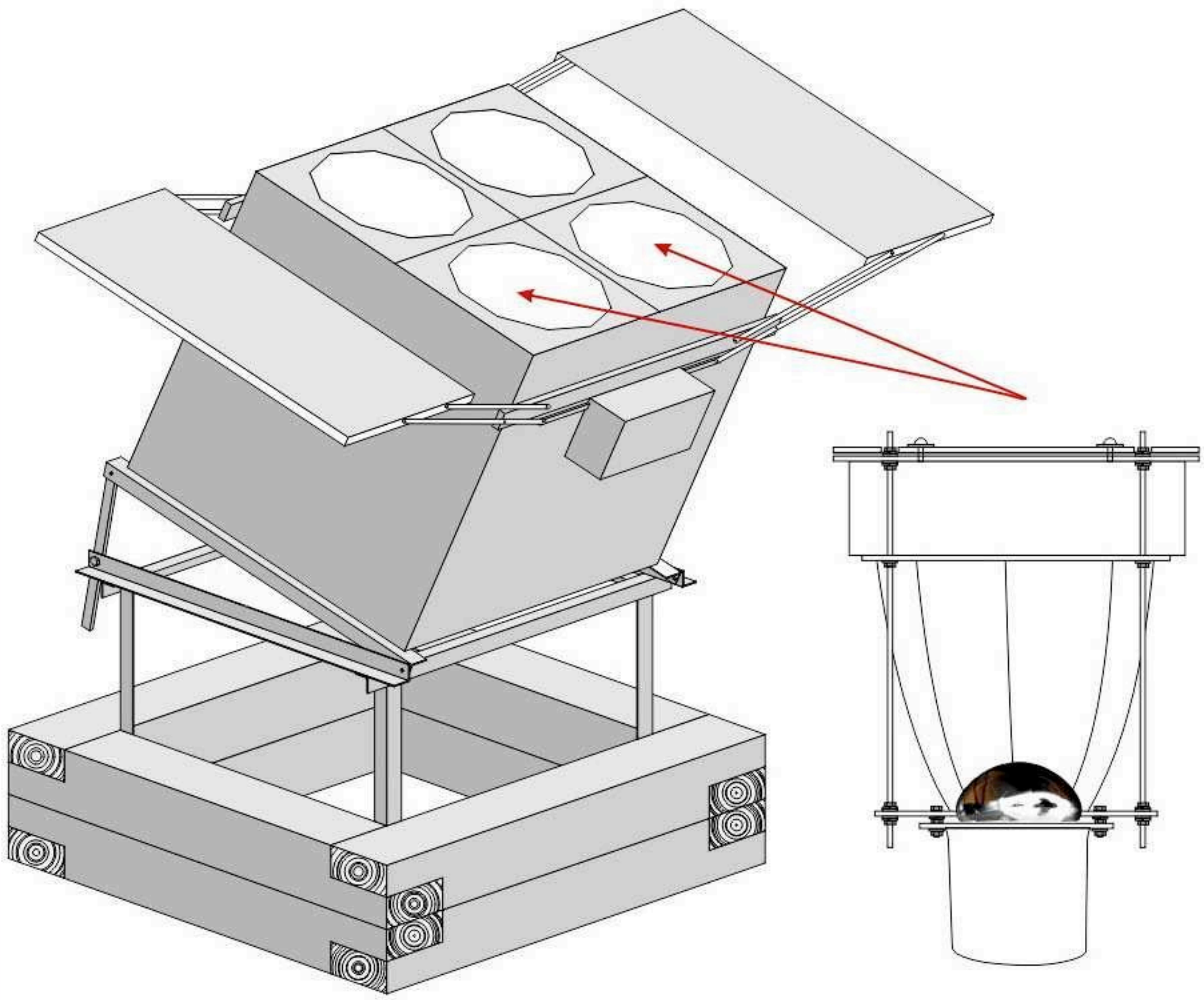
Since 2014

- Total: 28 stations
- spacing 100-150m
- 0.25 km²
- Tilting mode – 25° southwards

2016:

- First telescope
- Hybrid timing+imaging
  Next talk:
  TAIGA, L. Kuzmichev

HiSCORE = TAIGA timing stations



- Four 8" PMTs
- Winston cones, light collection 0.5 m²
- FoV ~0.6 sr
- “Tilting” for extension of sky coverage
- GHz readout
- **Sub-ns** array-wide time synchronization

TAIGA timing stations

- Four 8" PMTs
- Winston cones, light collection 0.5 m²
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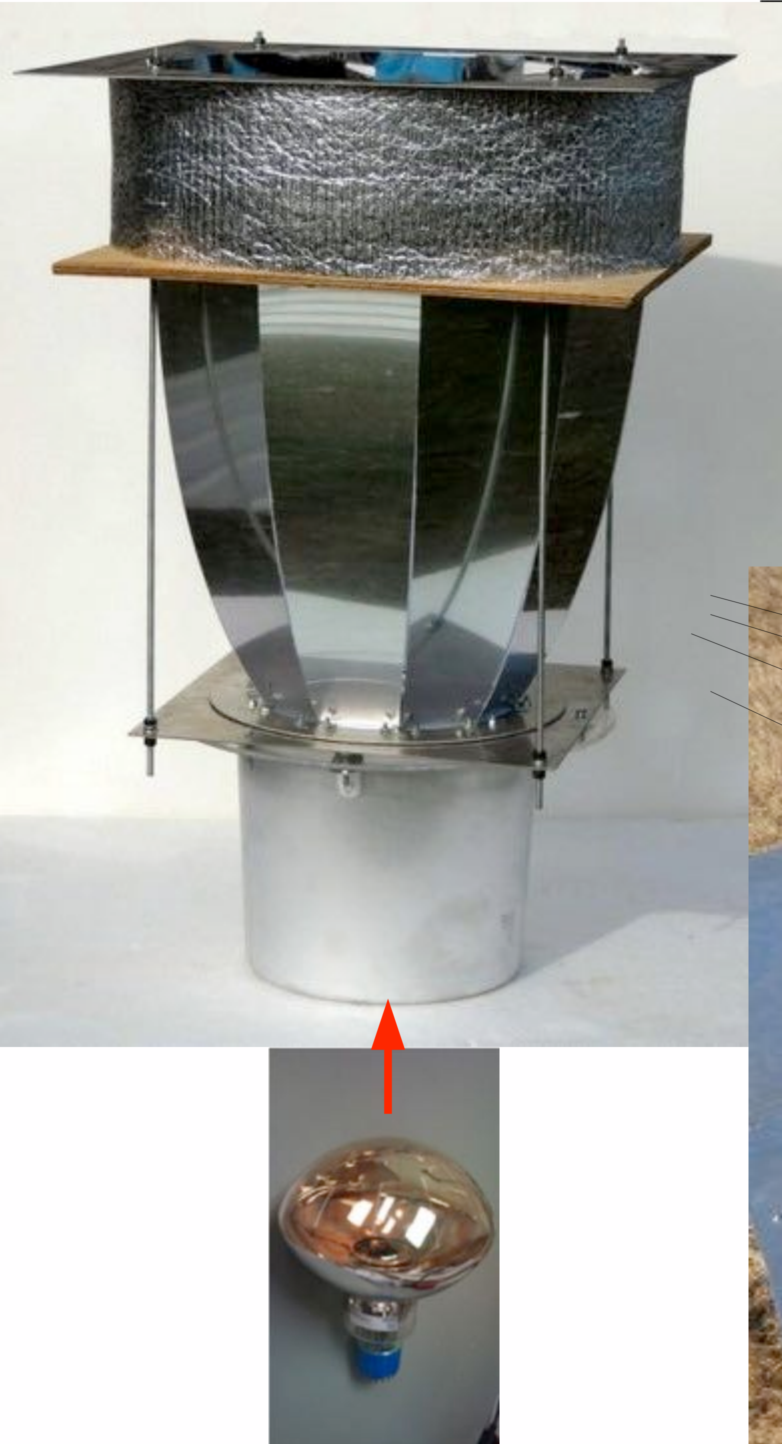
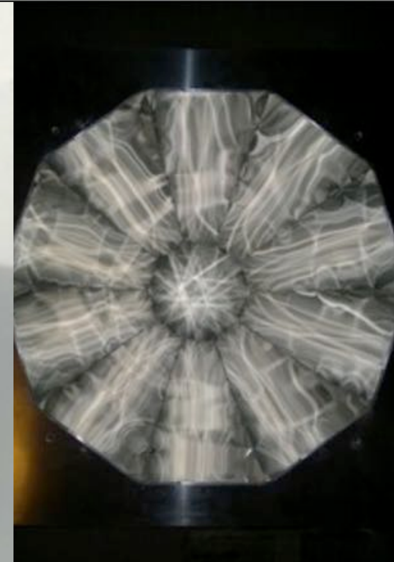
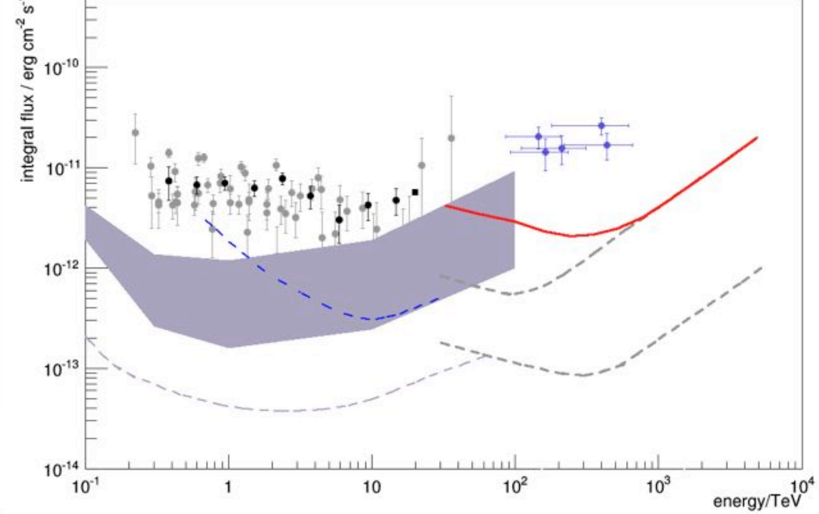
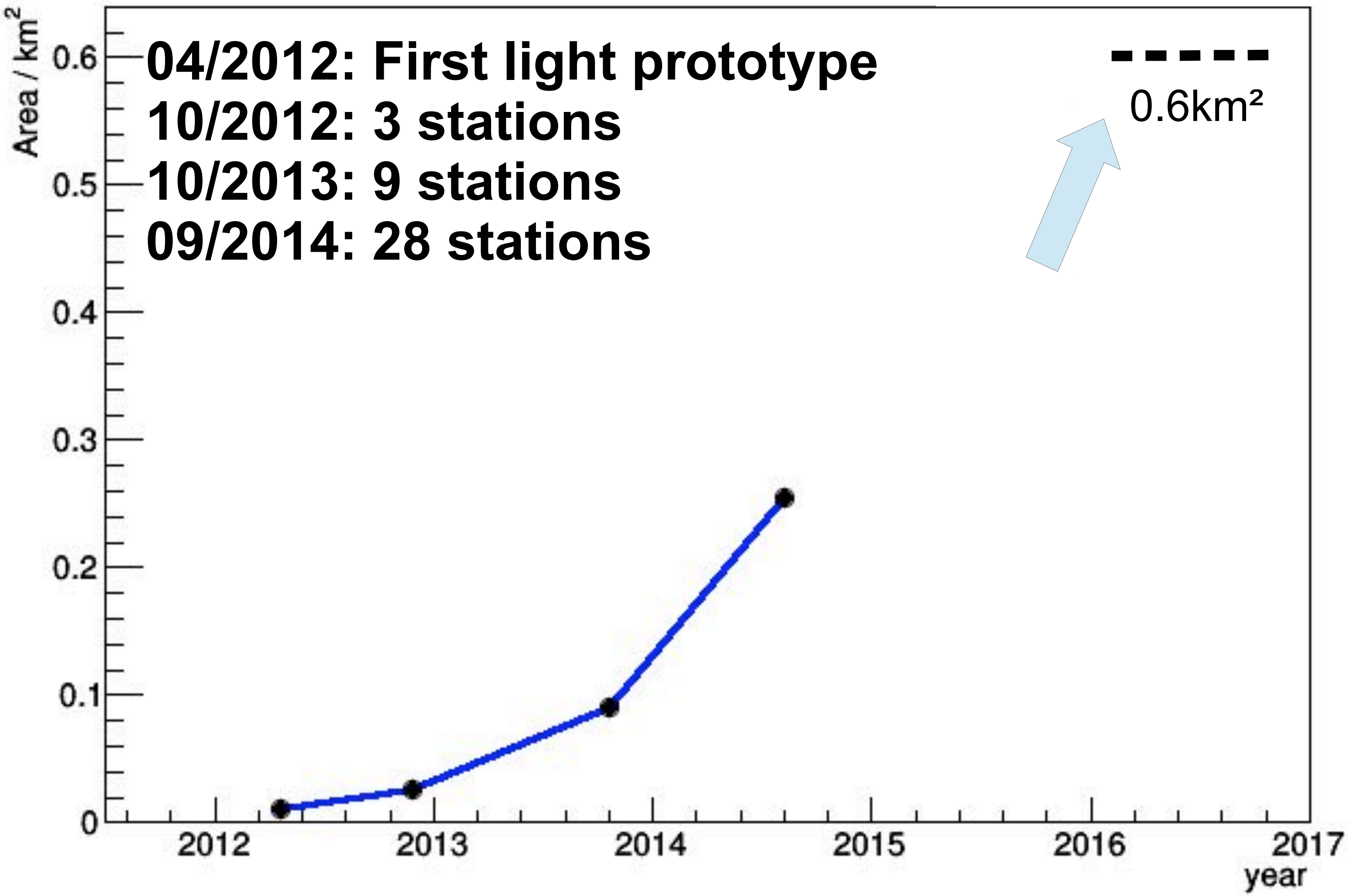




Evolution of effective area





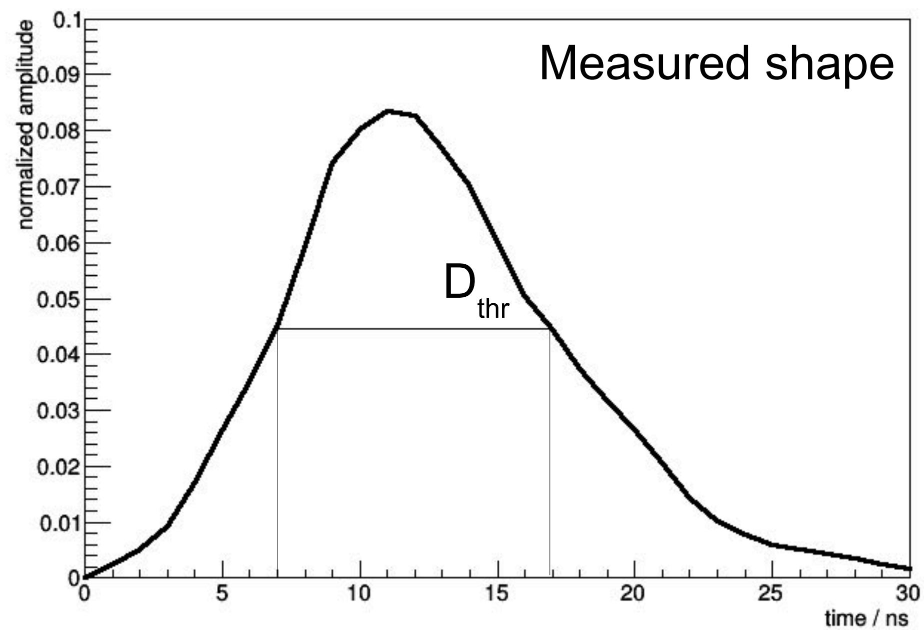
HiSCORE

Comparison of Monte Carlo simulation to Real Data

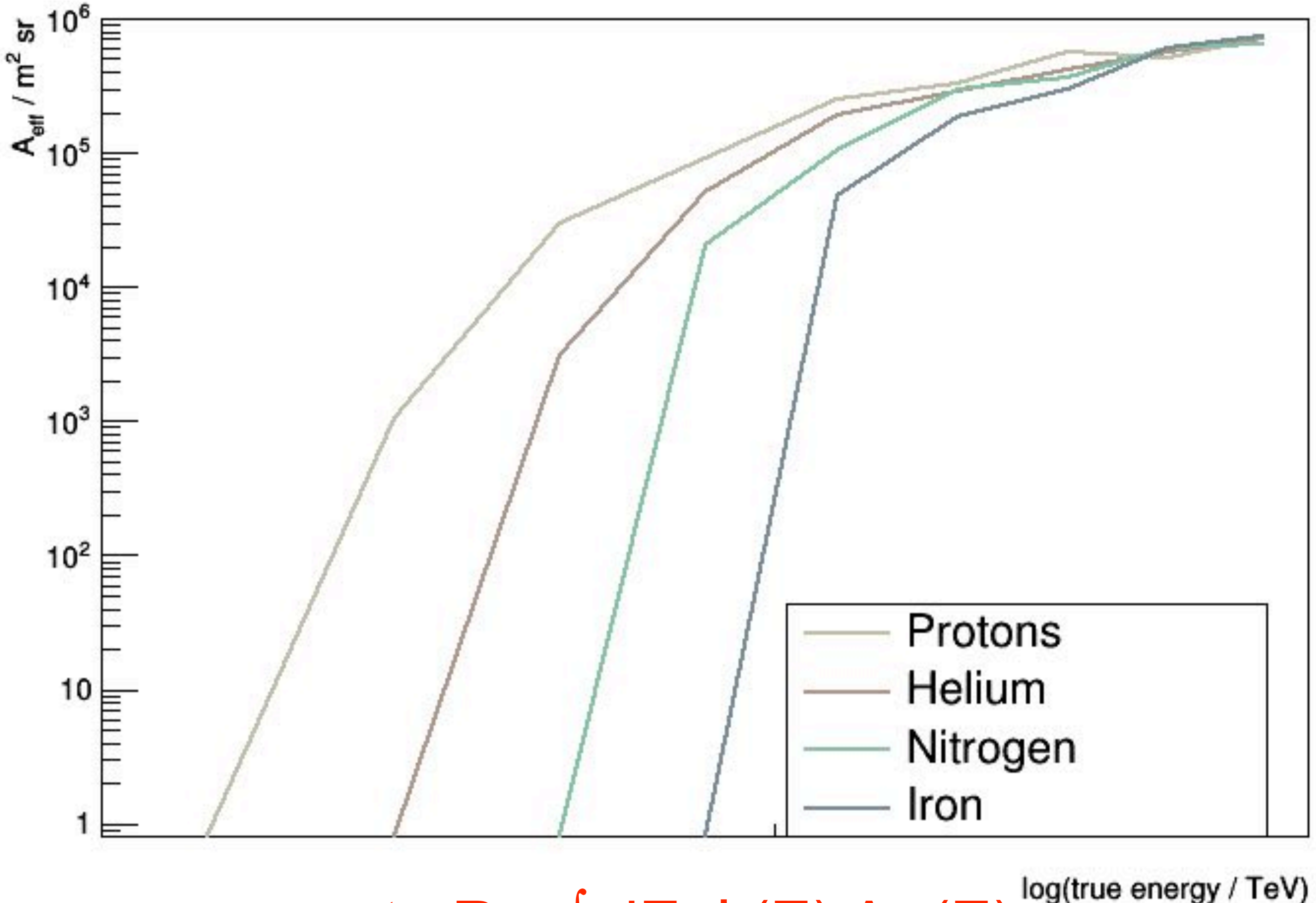
MC Simulation

- **Air showers** CORSIKA v6990, protons, He, N, Fe
- **Detector-simulation** sim_score:
  full simulation based on iact-package
  - Winston cone ray tracing
  - Atmospheric transmission (MODTRAN)
  - PMT quantum efficiency
  - Analog sum trigger, requiring sum > Dthr during τ ns
  - Night sky background simulation
  - Single p.e. pulse shaping

Astroparticle Physics, 2014arXiv1403.5688T



Effective trigger area

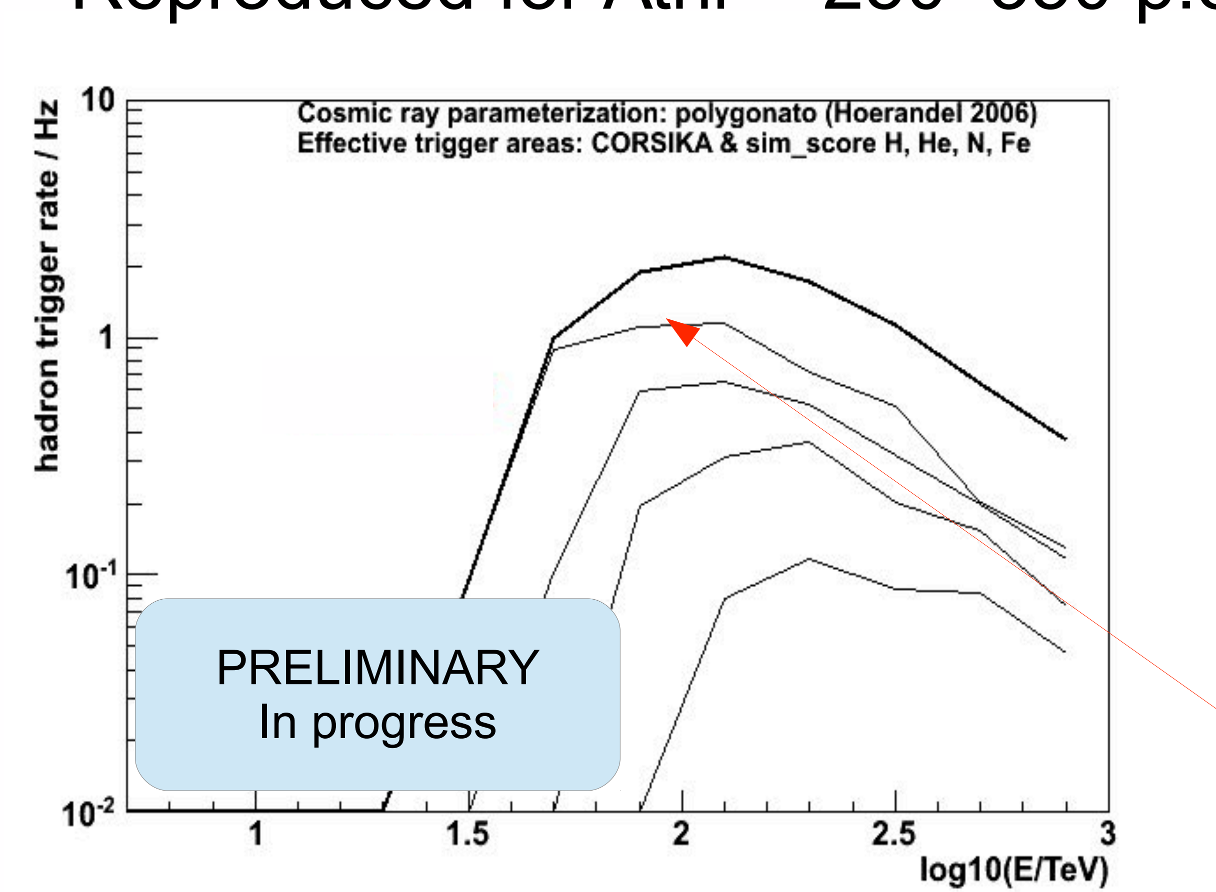


rate $R = \int dE\ \Phi(E)\ A_{eff}(E)$

$\Phi(E)$: polygonato model (Hörandel 2003) & ATIC p/He parametrization

Data – MC comparison

- Array trigger rate: minimum 4 stations triggered
  - 10-18 Hz
  - Reproduced for Athr = 250–350 p.e.



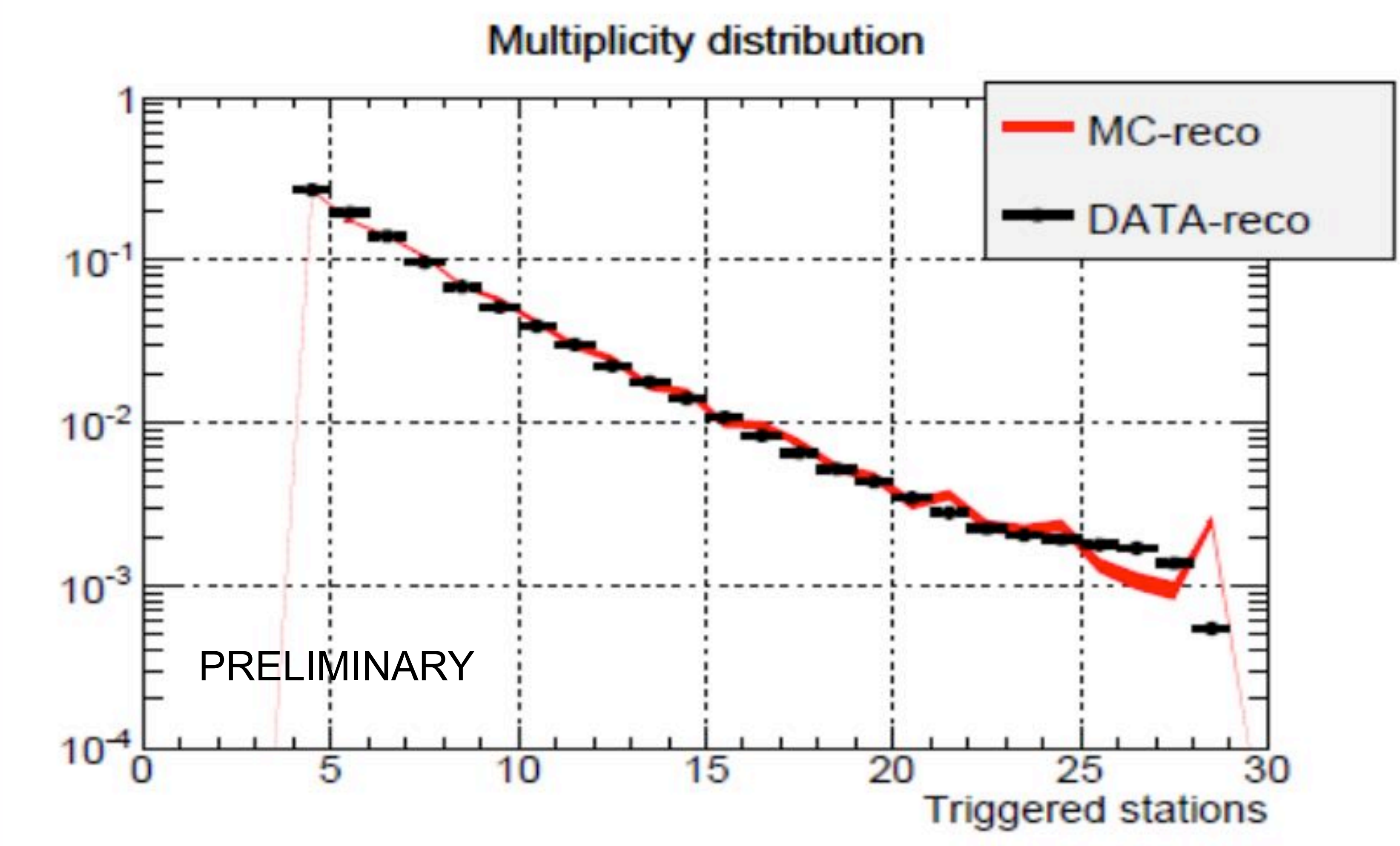
Single station rates:

8-12 Hz from data
10 Hz from simulations

Proton threshold

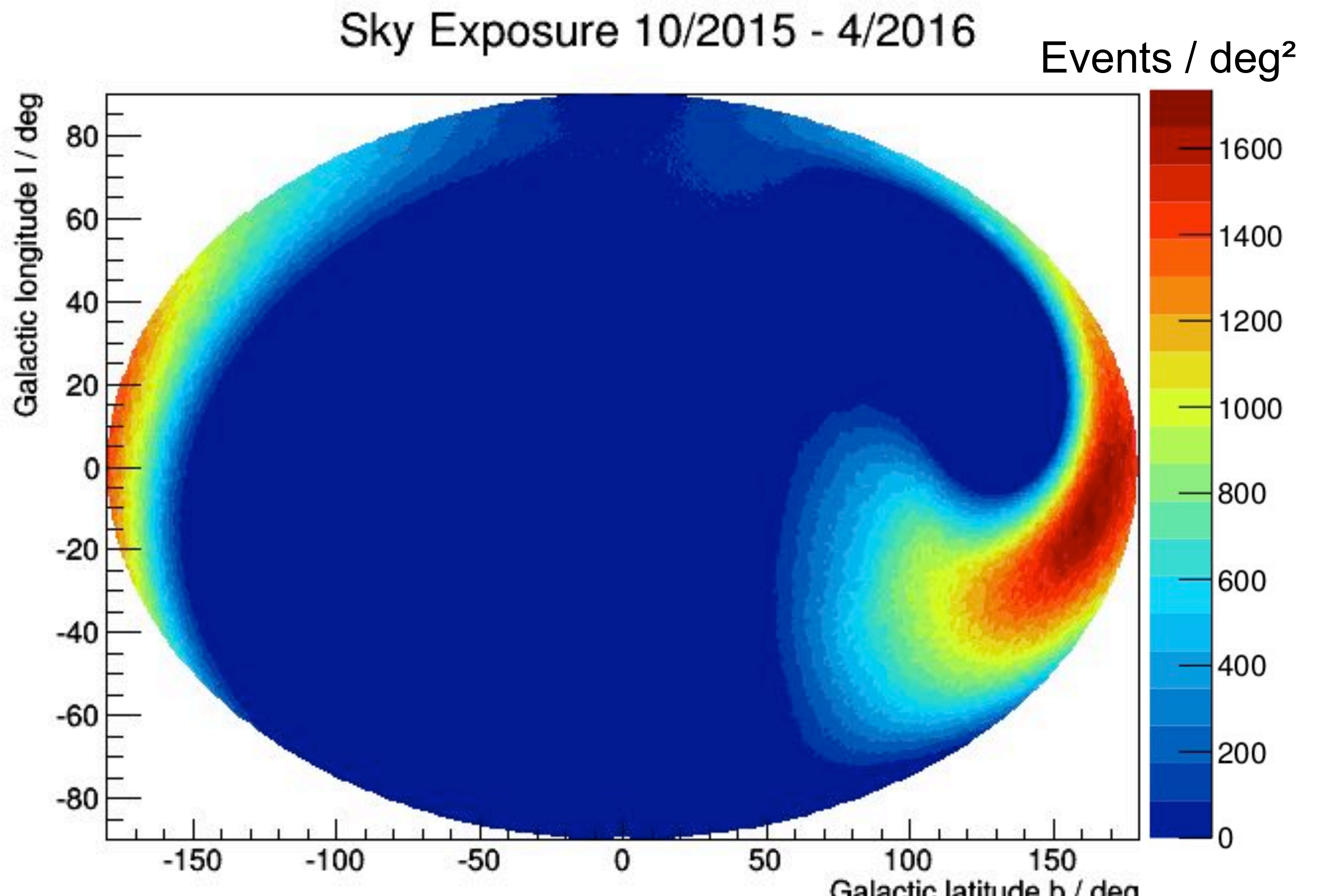
Data-MC comparison

- Multiplicity 28 station array



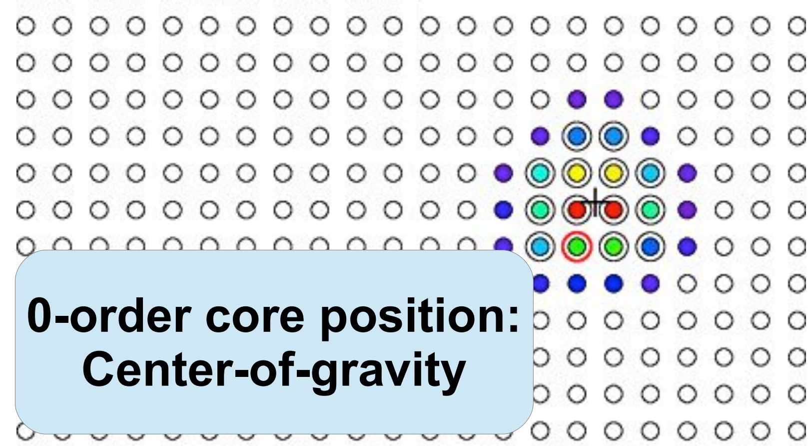
Data and Exposure

- Observations during commissioning phase of 28-station array October 2015 – April 2016
- Total 250 h observation time
- ~10^7 events

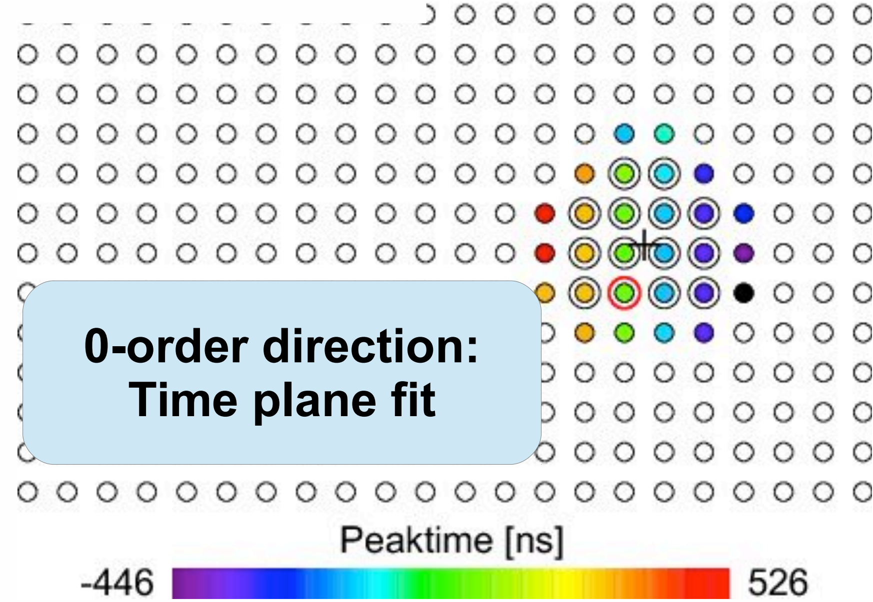


Event Reconstruction

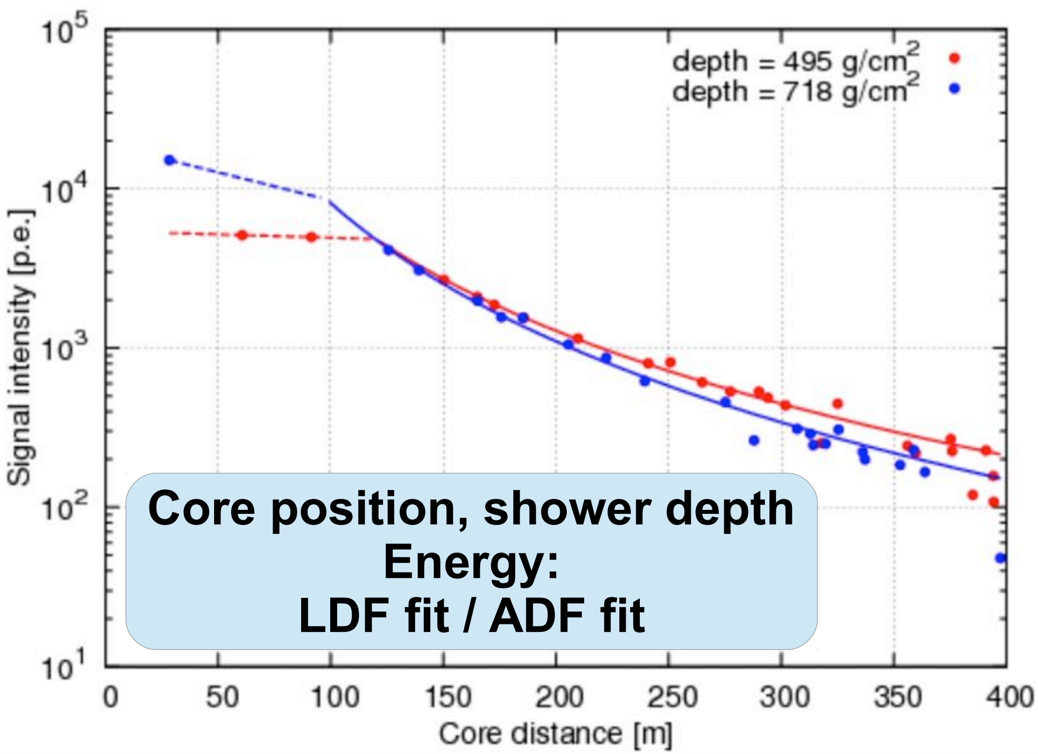
Tunka-133 [Berezhnev et al. 2012NIMPA.692...98B]
HiSCORE [Hampf et al. 2013NIMPA.712..137H]



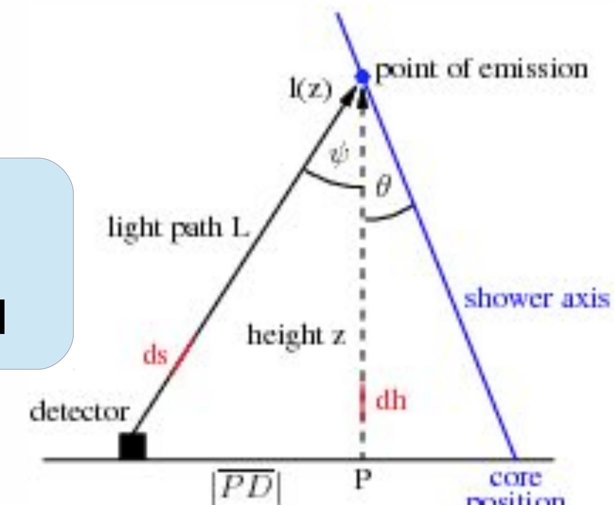
0-order core position:
Center-of-gravity



0-order direction:
Time plane fit

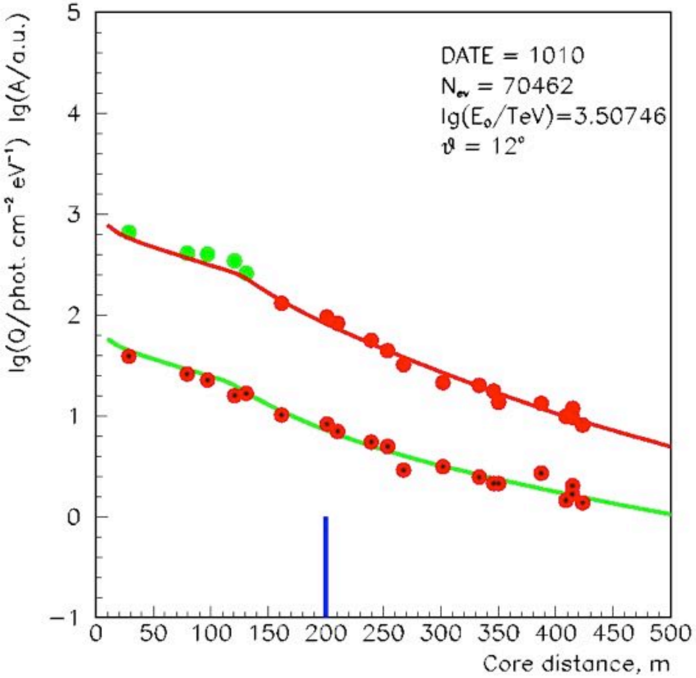


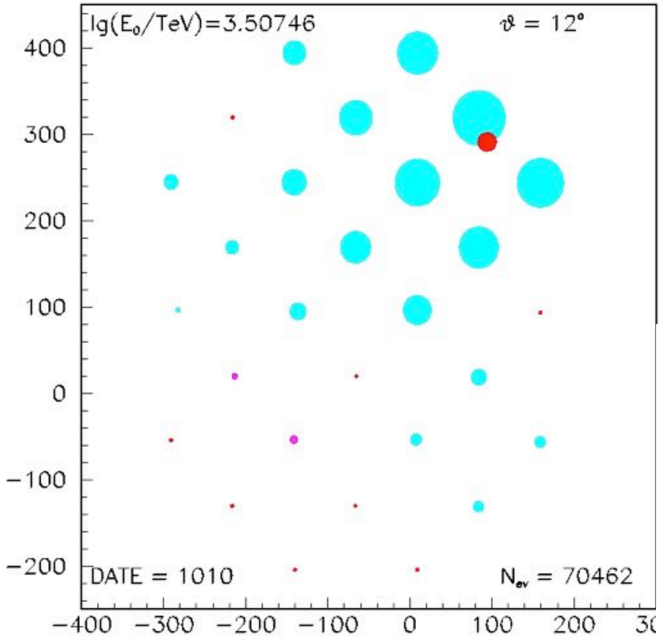
Core position, shower depth
Energy:
LDF fit / ADF fit

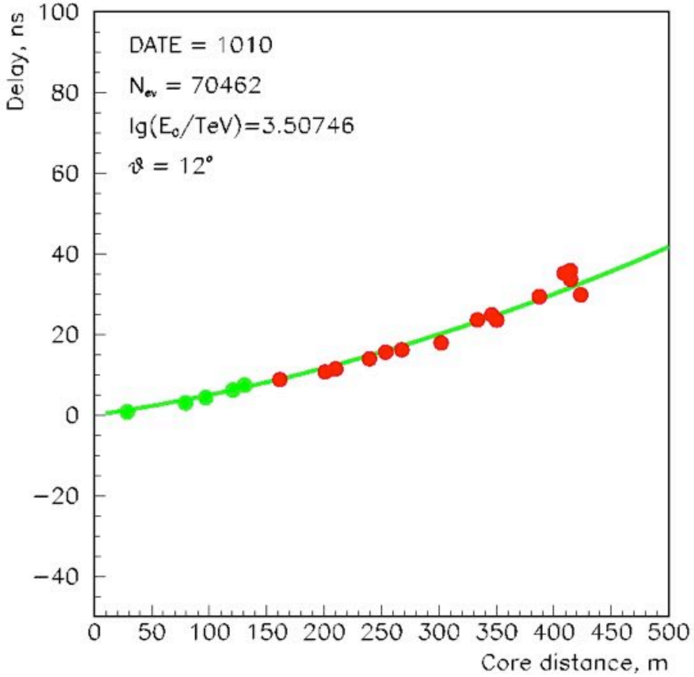


Direction:
Cone fit
Timing model

Event reconstruction



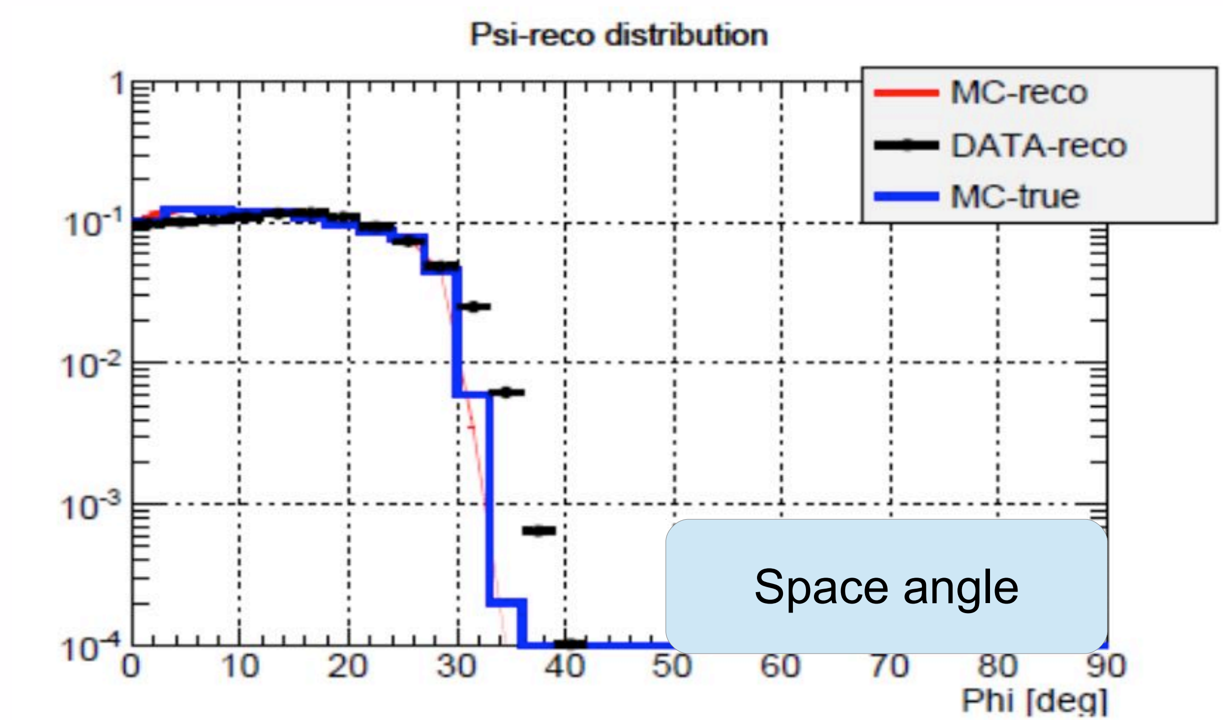


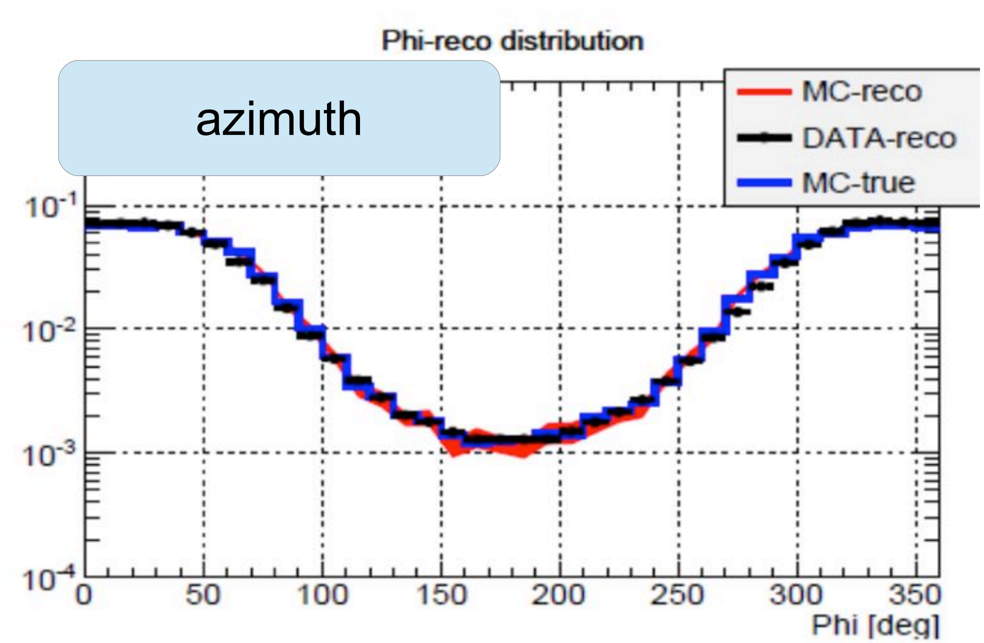


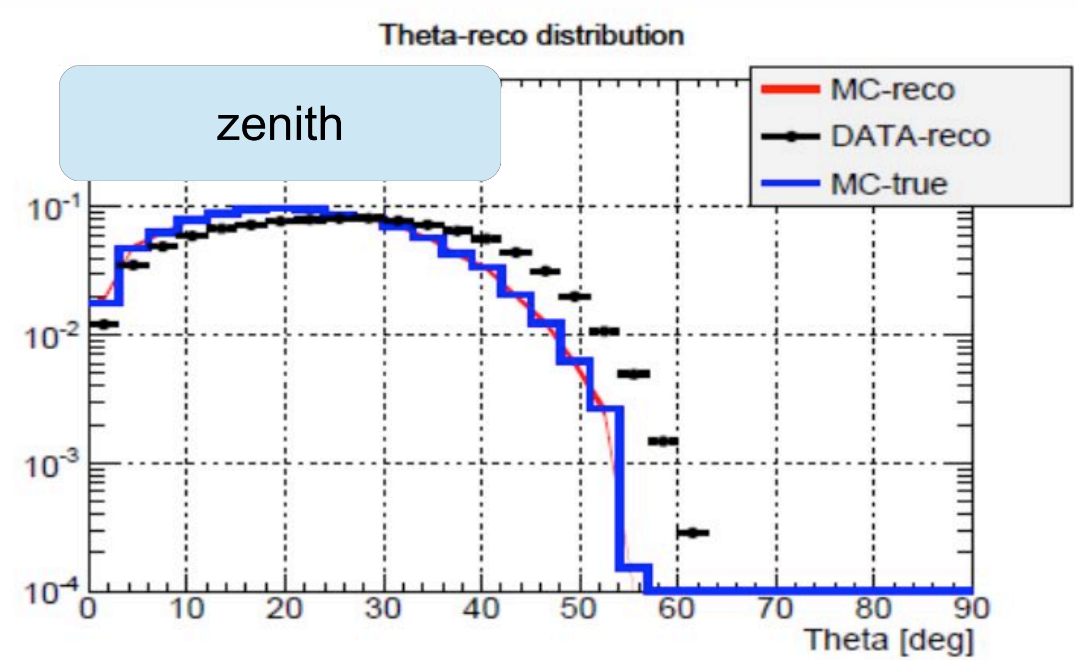
Reconstruction

Reconstructed direction

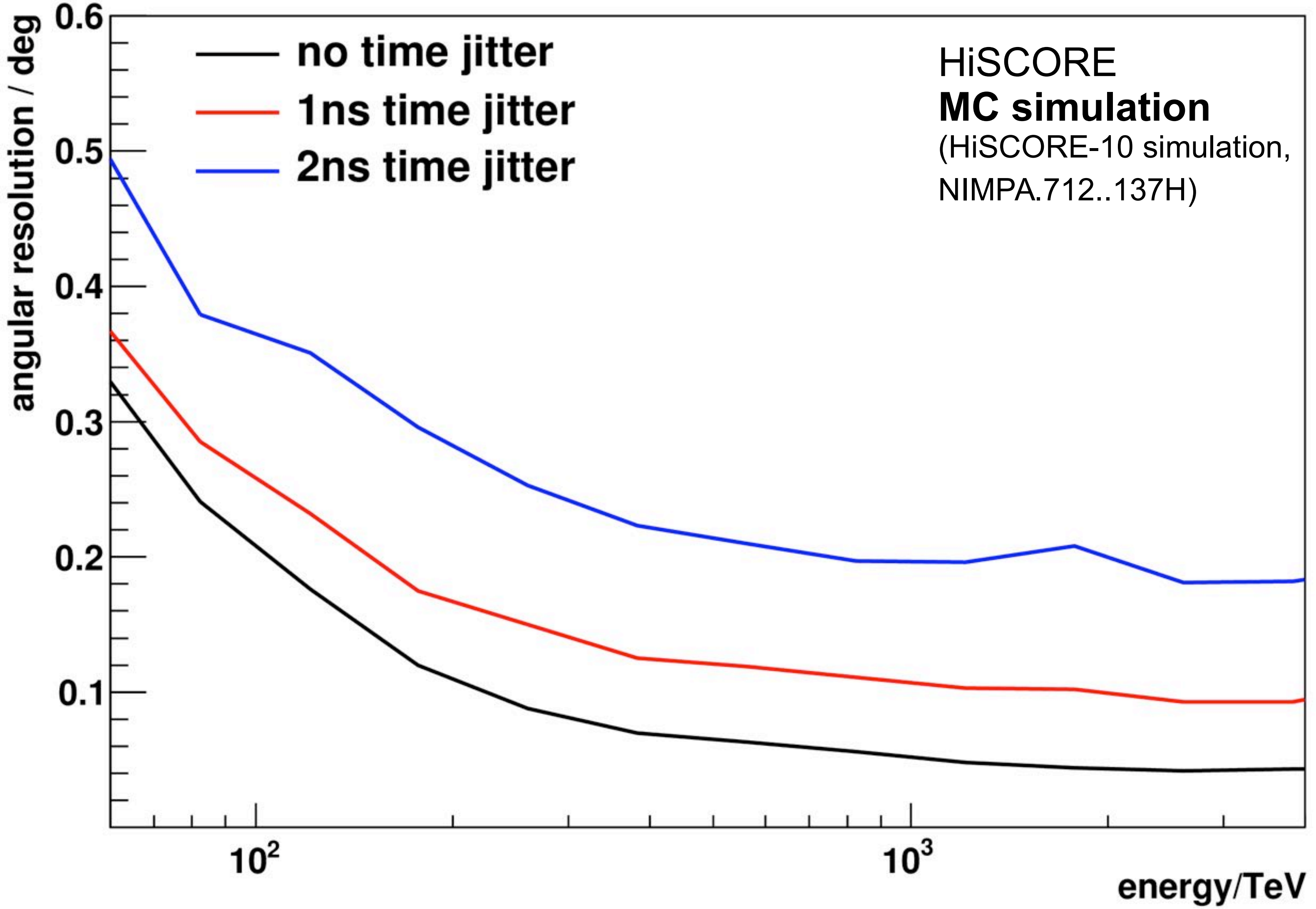
Data & MC





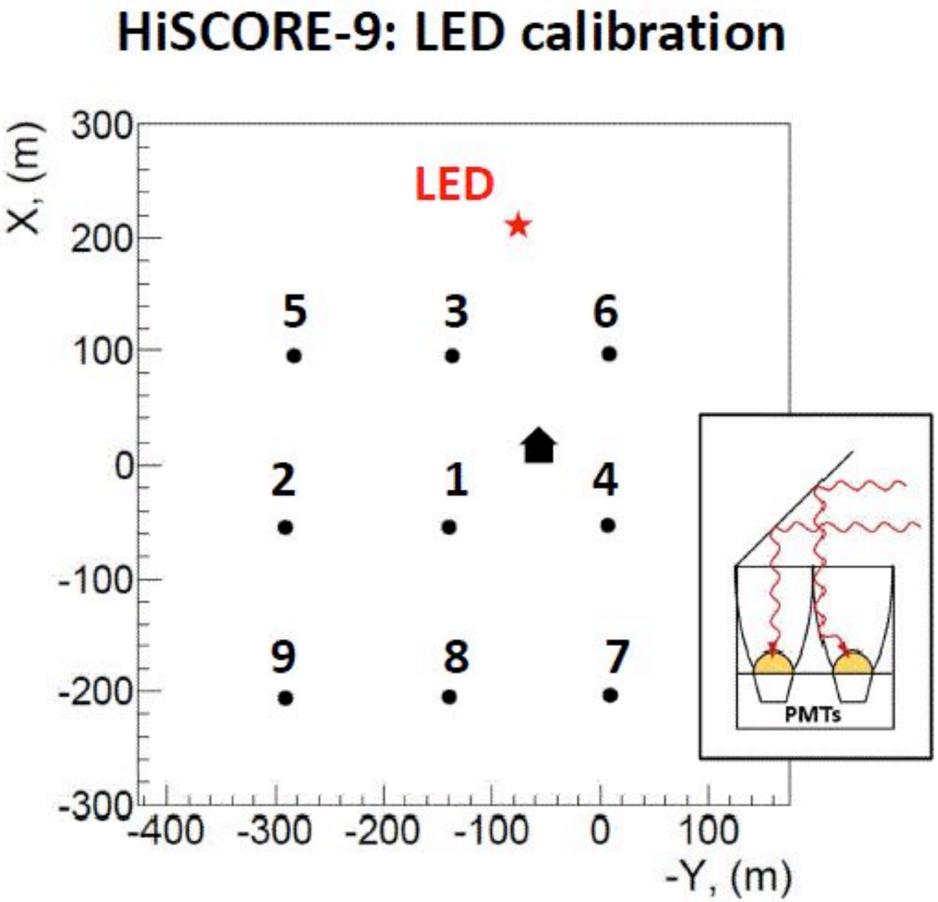


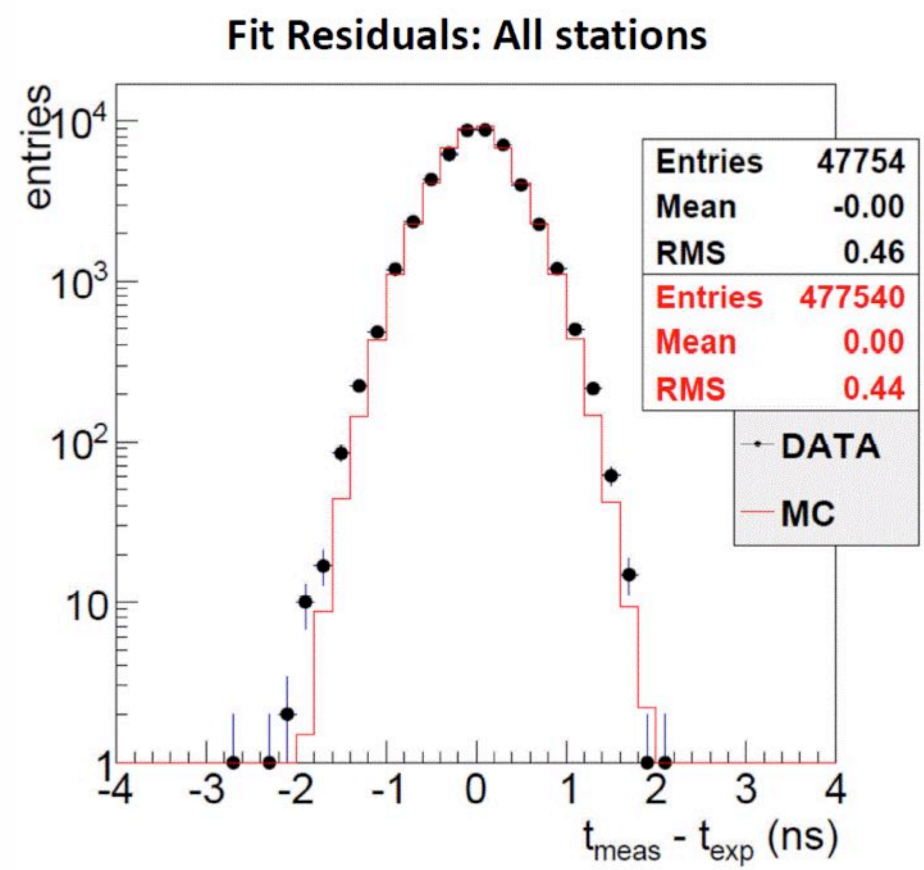
Angular resolution



Crucial: relative time-synchronization <1ns

Time calibration

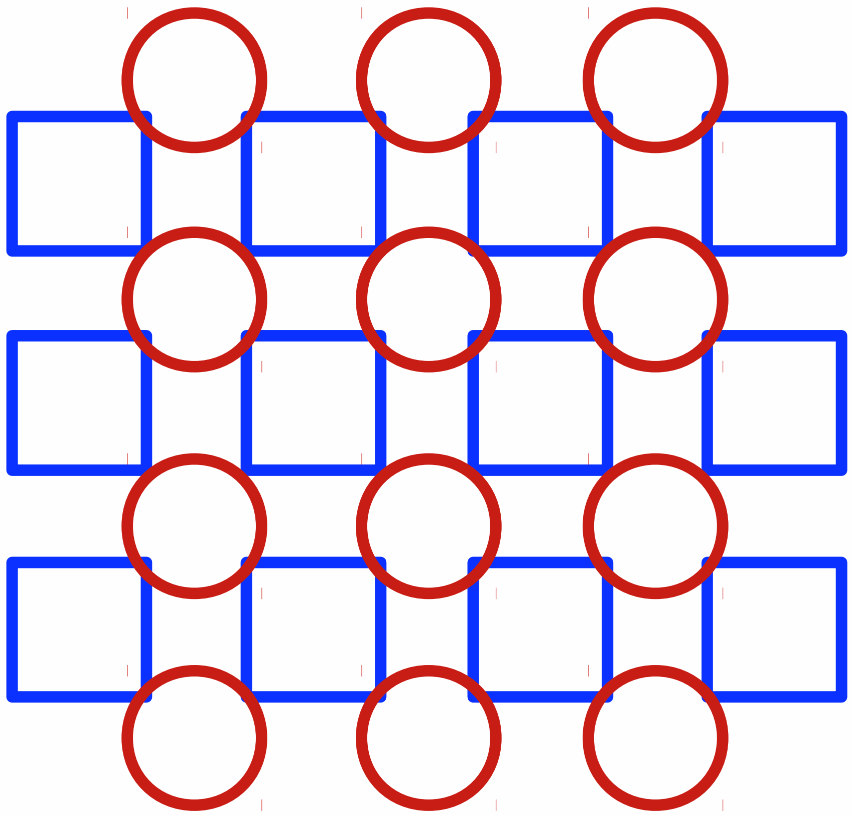




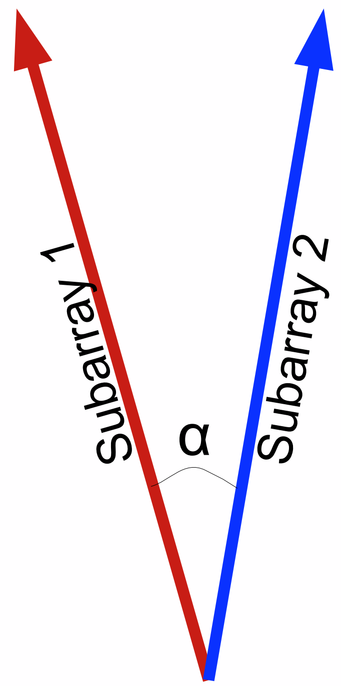
2013 HiSCORE-9
2 independent t-cal systems yield comparable accuraccies (<0.5 ns)

See, e.g. R. Wischnewski, this Conference (Poster session)

Resolution chessboard method



Reconstruction using two different subarrays

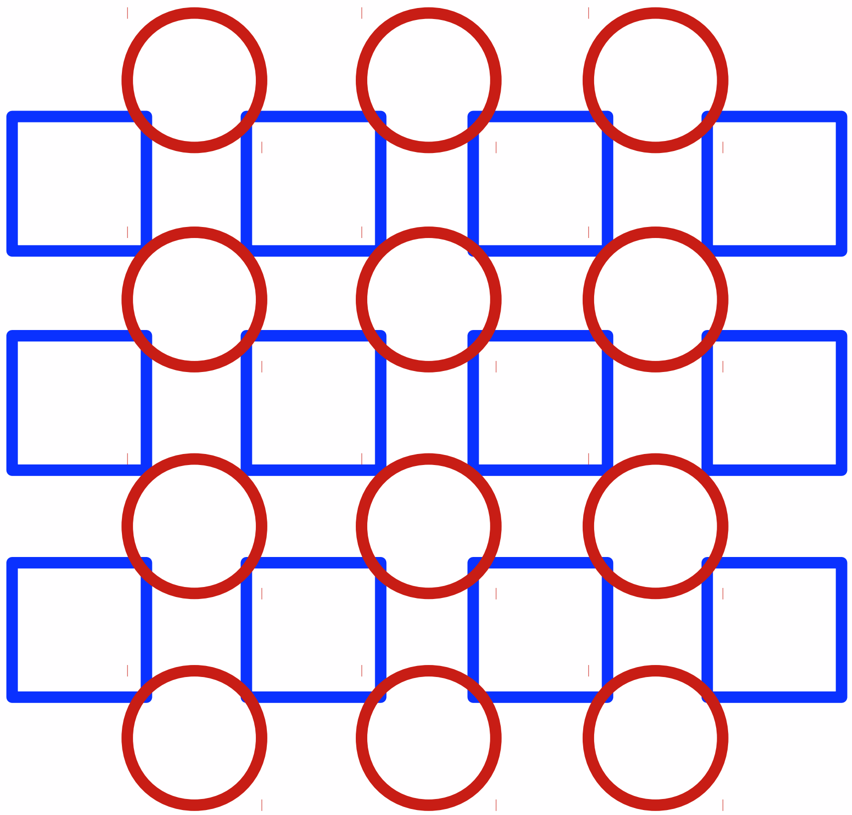


Chessboard direction:

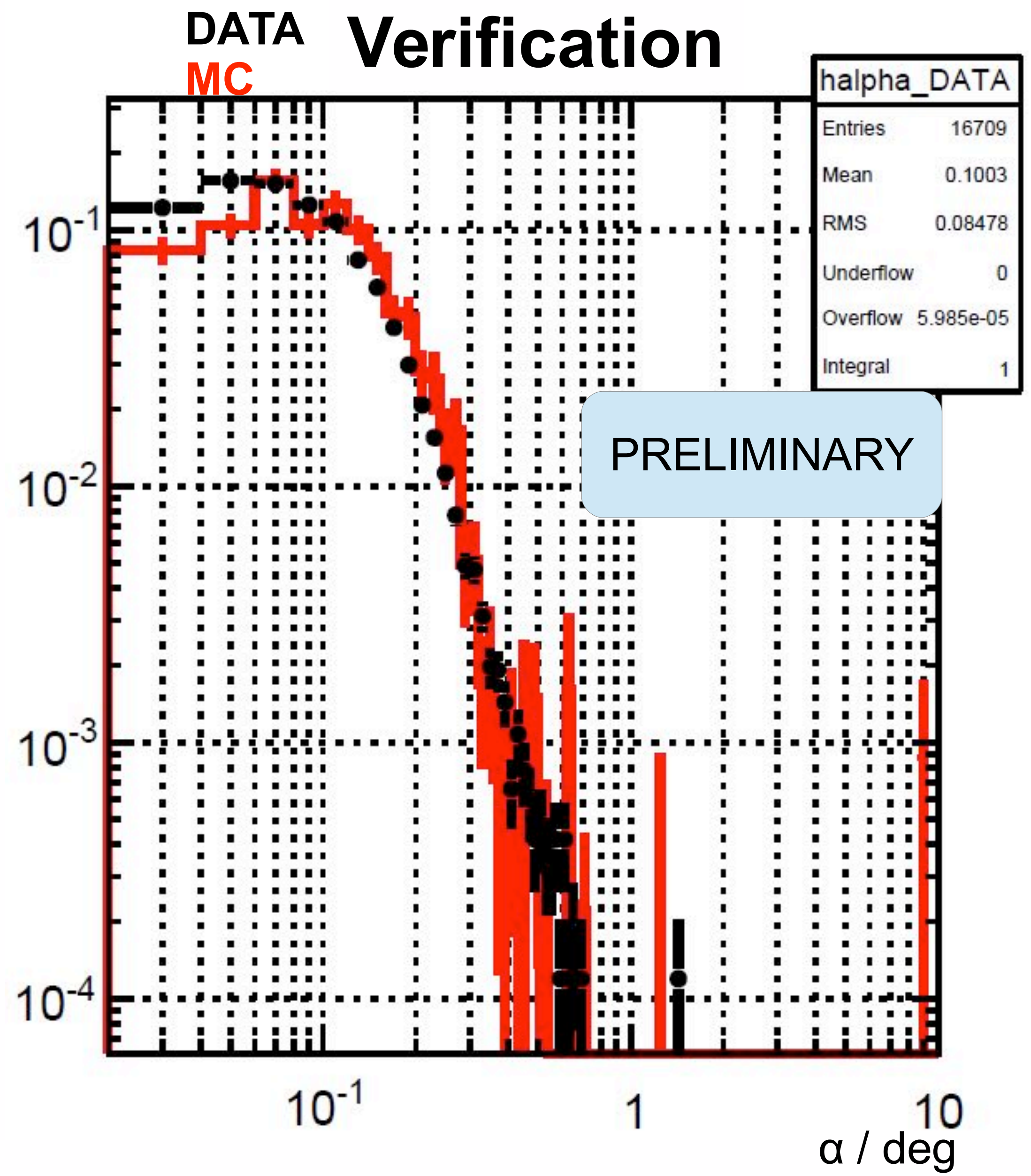
Resulting angle α

Tested for 9-station and 28-station array

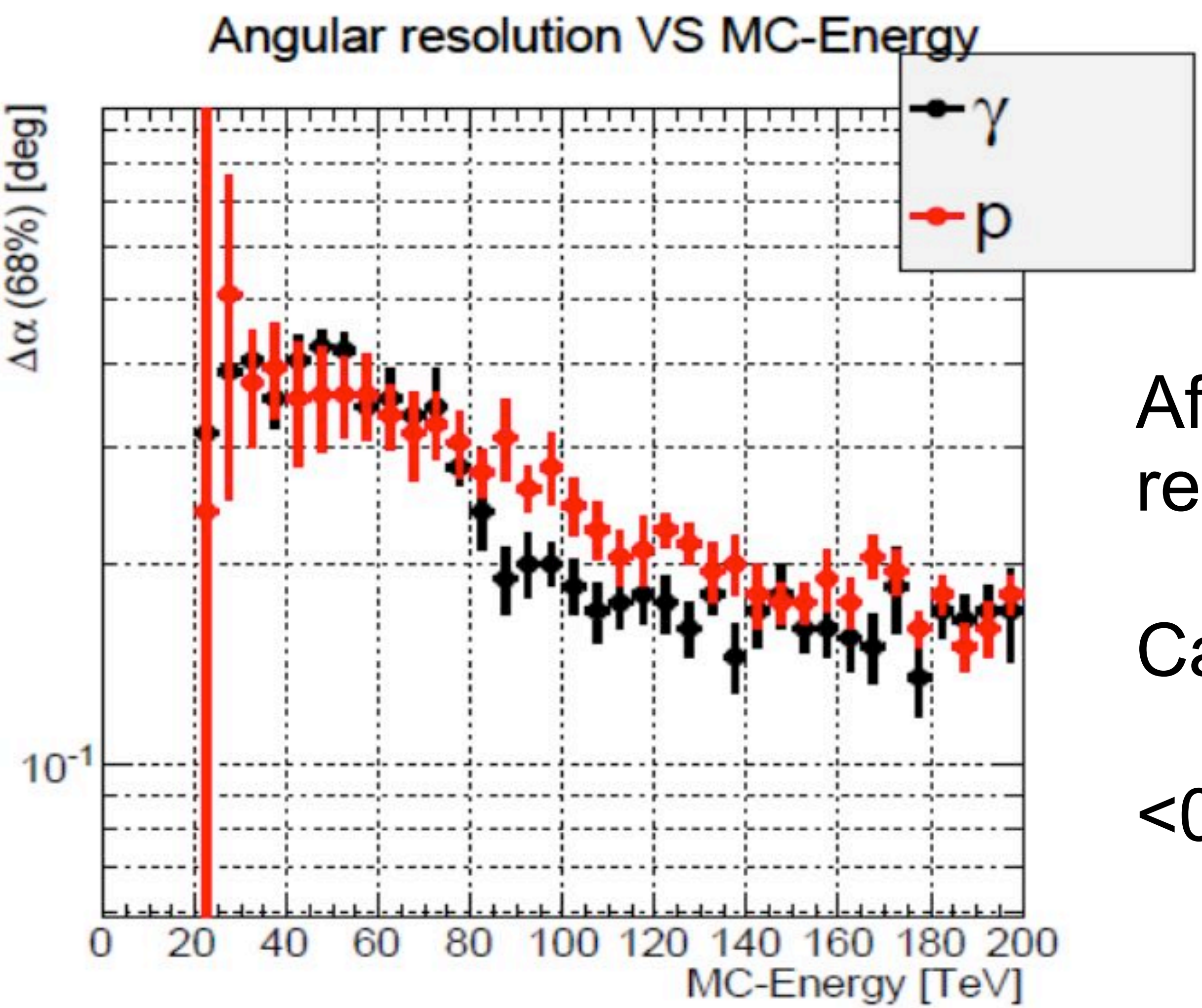
Resolution chessboard method



[Reasonable agreement between MC and data]()



Angular resolution 28 station array



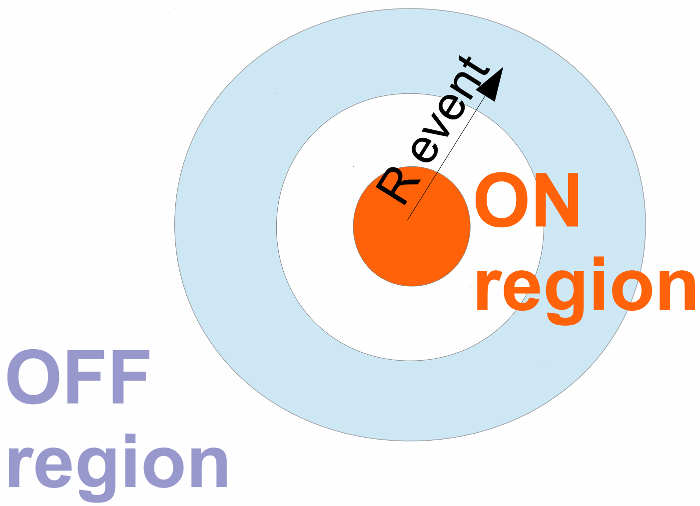
After verification of MC resolution in data:

Can trust MC resolution

<0.2° E>100TeV

Background for pointsource search

- **Ring background model**
  - **On source:** < 0.4°
  - **Off source:**
    from ring around source position 1.6°< R < 2.4°

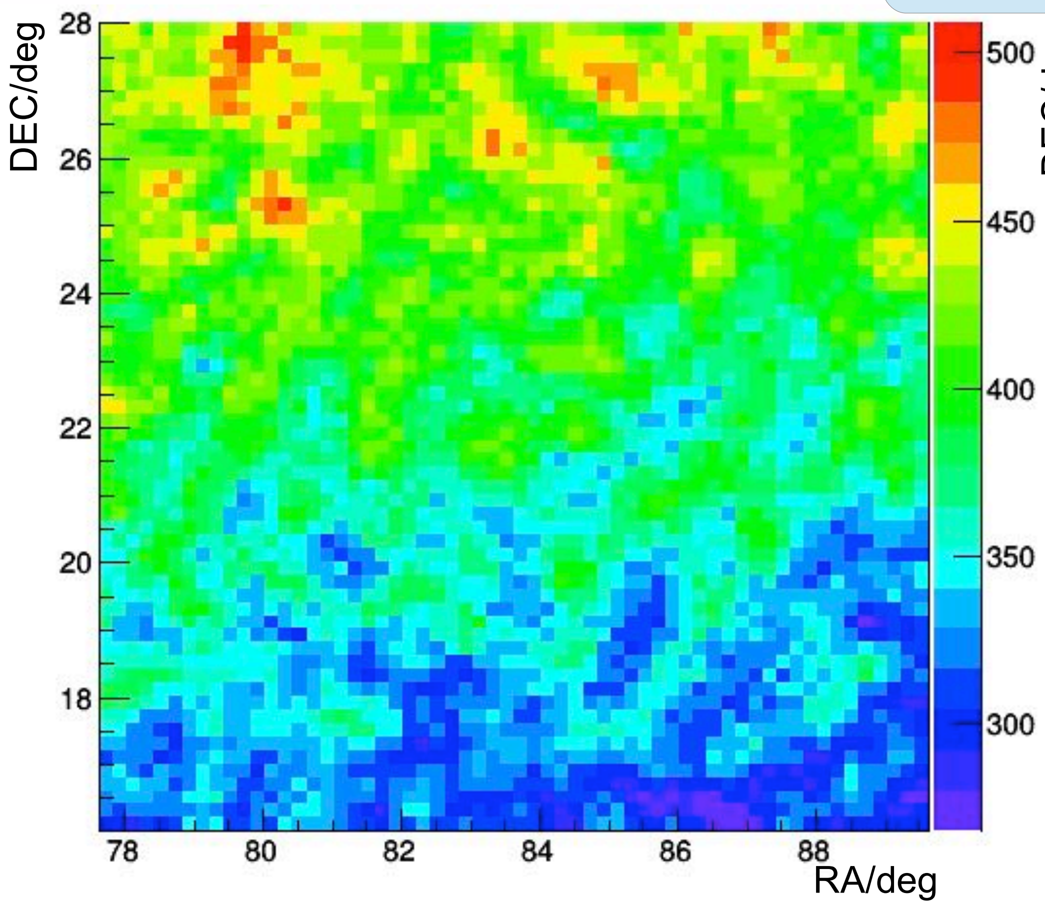


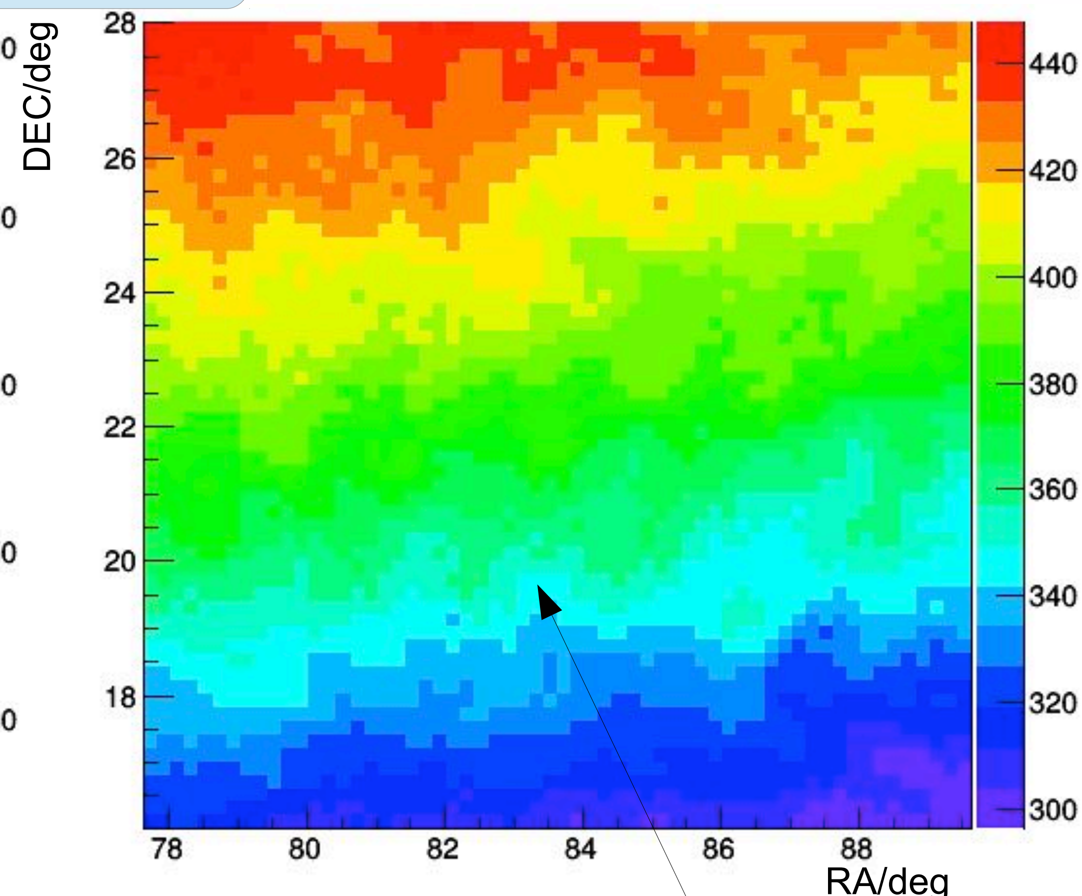
- **Testing the background model**
  - **Data blinding:**
    local ra/dec randomization by Gaussian width σ= 1°
  - Apply P.S. search to blinded data
  - Expectation: normal Gaussian distribution of significances in field of View

Background for pointsource search

BLINDED DATA

PRELIMINARY

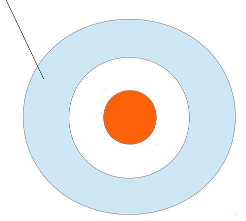




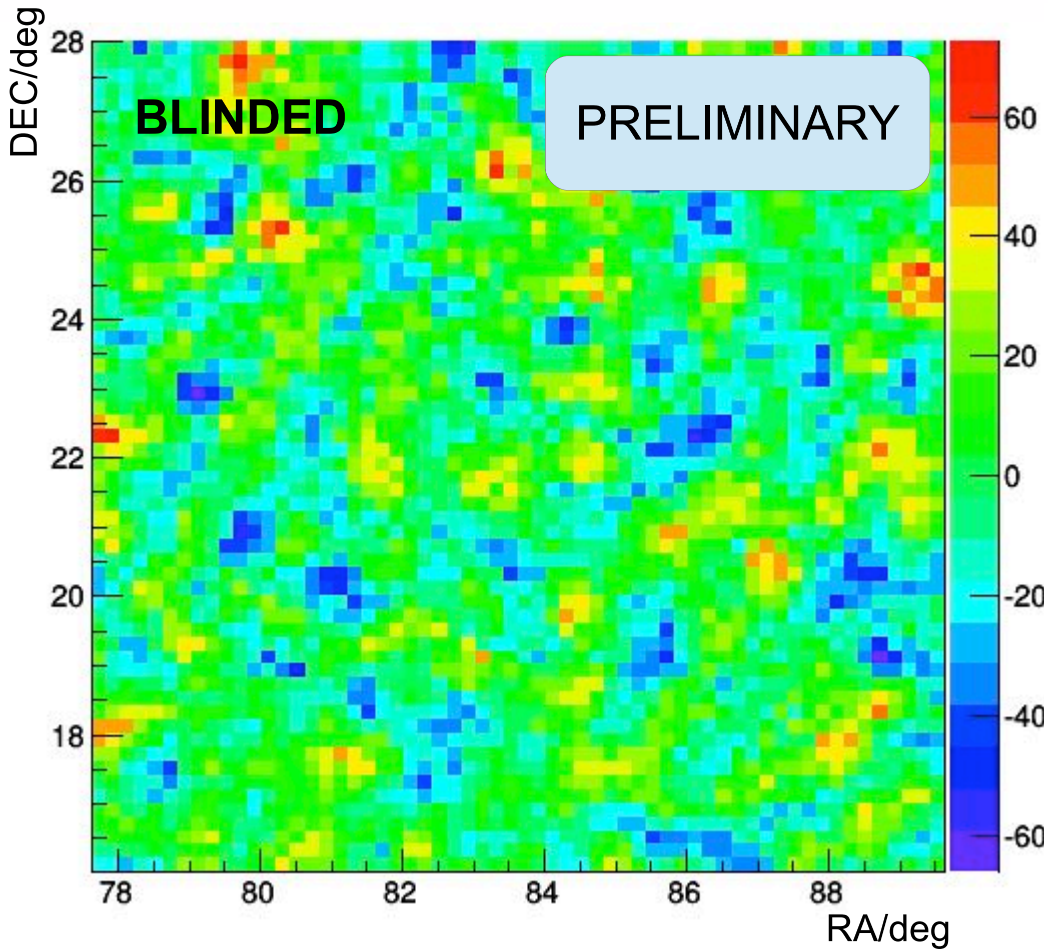
Non count map **α Noff count map**

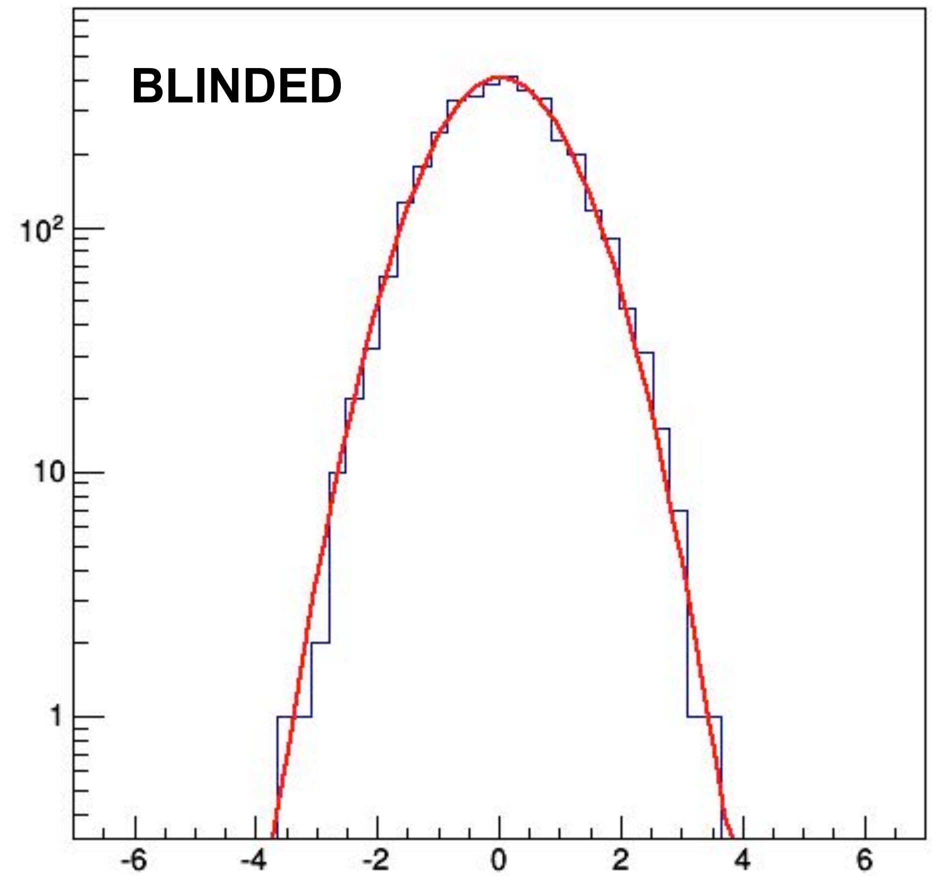
Oversampled skymaps 6° x 6°

Preselection 10° x 10° (reducing computing requirement)



Background for pointsource search





Excess skymap

Excess = Non – α Noff (α = 0.05)

Blinded data

Significance following Li&Ma, Eq. 9

Significance distribution in foV

Crab Nebula data commissioning season

- ~60 h good weather exposure on Crab Nebula
- 10^4 events within 3 deg of Crab Nebula
- Preliminary analysis O(20) events (bg ~380, not significant)

→ As expected with 0.25 km² prototype sensitivity

→ No analysis cuts / not optimized analysis

→ Potential for improvement in future:

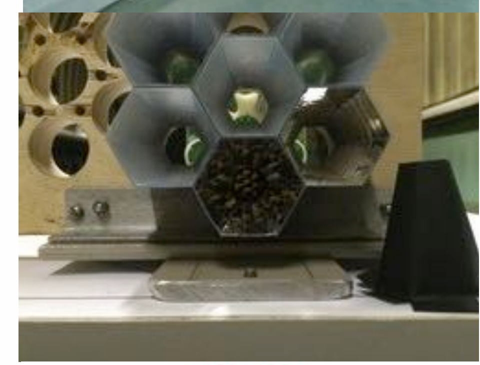
  - larger area → 0.6 km²
  - optimized analysis
  - TAIGA: +IACT

Preliminary analysis !

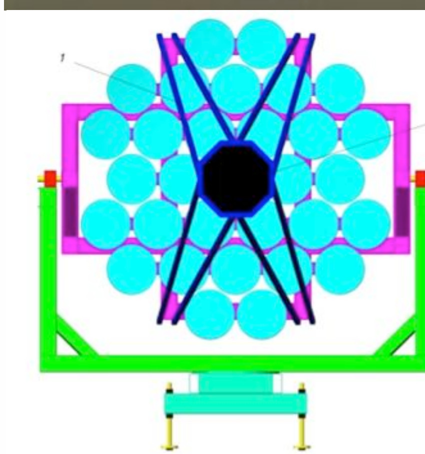
Summary

- UHE gamma-ray Astronomy with new hybrid imaging+timing approach

  Goal: 10^{-13} erg cm^{-2} s^{-1} @ 100 TeV



- HiSCORE timing array 0.25 km² operational as part of **TAIGA**
- First results within expectations: on-track
- Doubling of area in 2016/2017
  → 0.6 km² / 58 stations
- Upcoming TAIGA-IACTs (next talk)

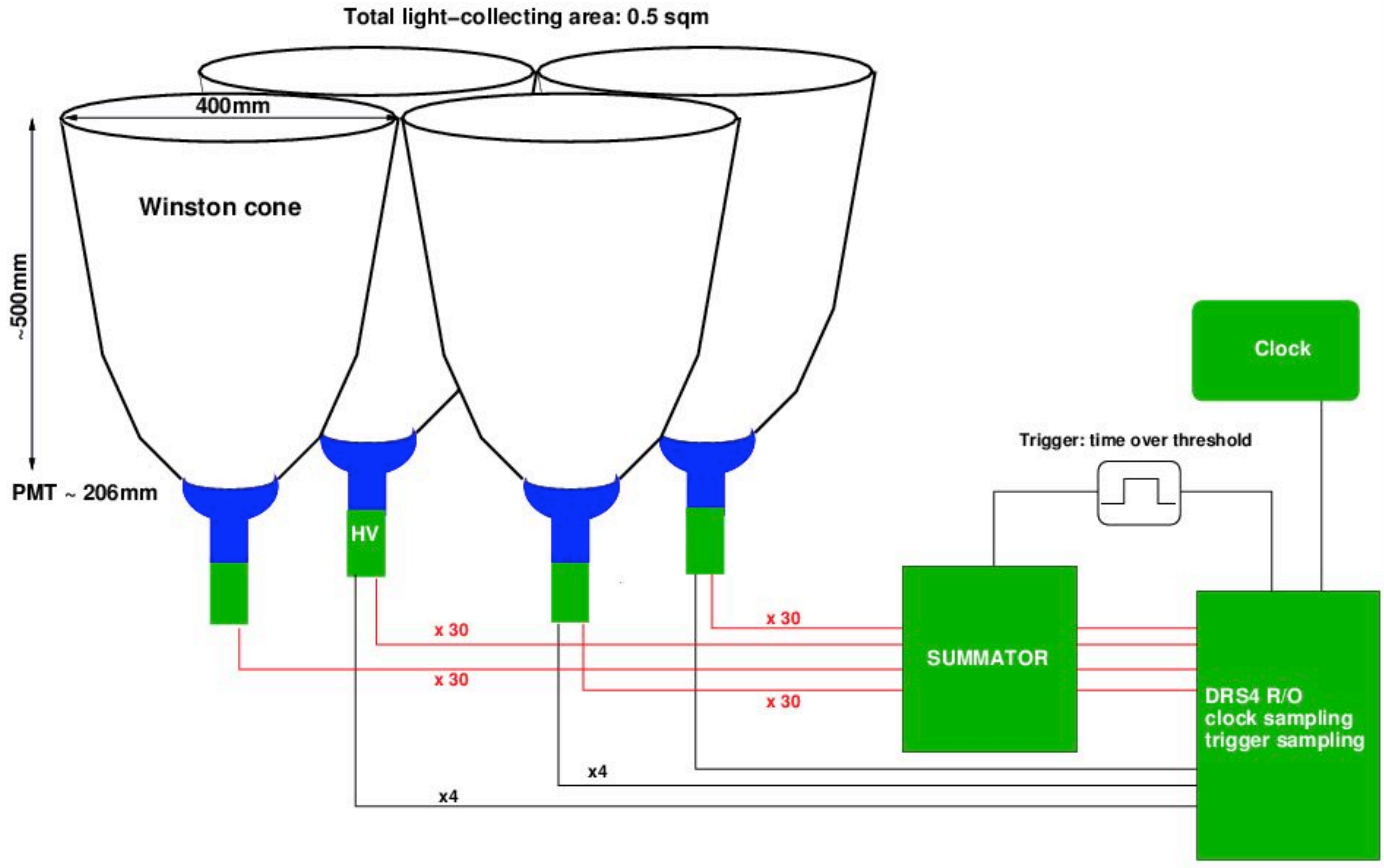


2016: “TAIGA-HiSCORE in the Tunka Valley: design, composition and commissioning”, to appear
2015: Journal of Physics: Conference Series (2015) 632 012042
2015: PoS(ICRC2015)1041
2014: Astroparticle Physics, 2014arXiv1403.5688T
2013 NIMPA.712..137H, arXiv:1302.3957
2013: ICRC 1146, 1158, and 1164
2011AdSpR..48.1935T, astro-ph/1108.5880
http://wwwiexp.desy.de/groups/astroparticle/score/
http://tunka-hrjrg.desy.de/

END OF TALK

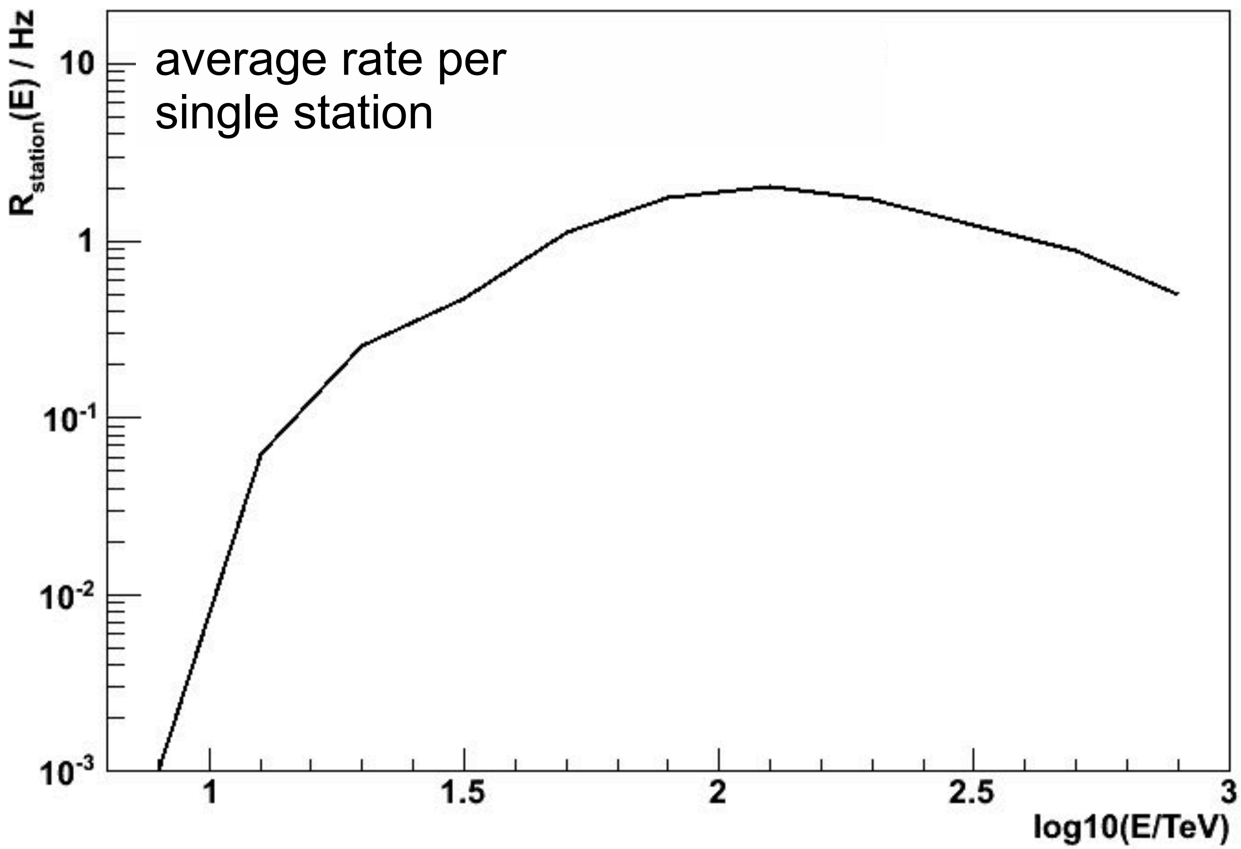
BACKUP

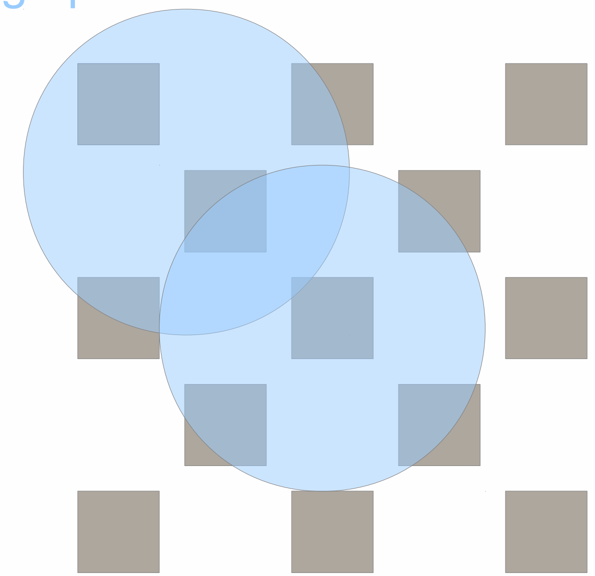
Triggering and Readout



Data – MC comparison

- Trigger rate: hadron-induced single station rate

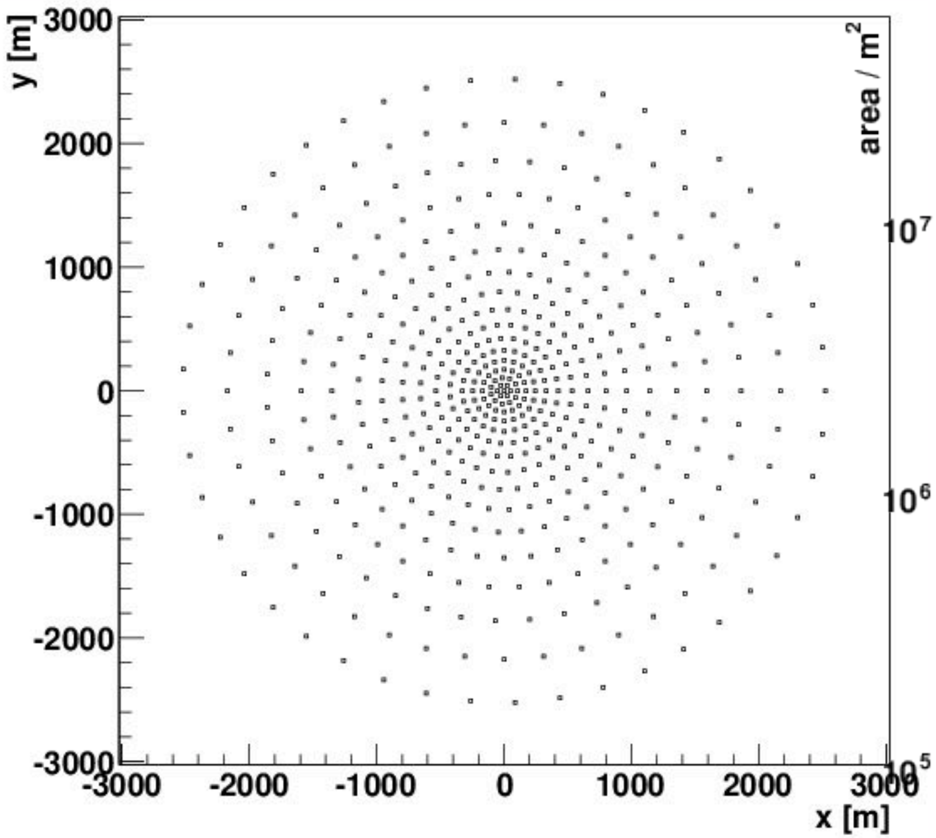


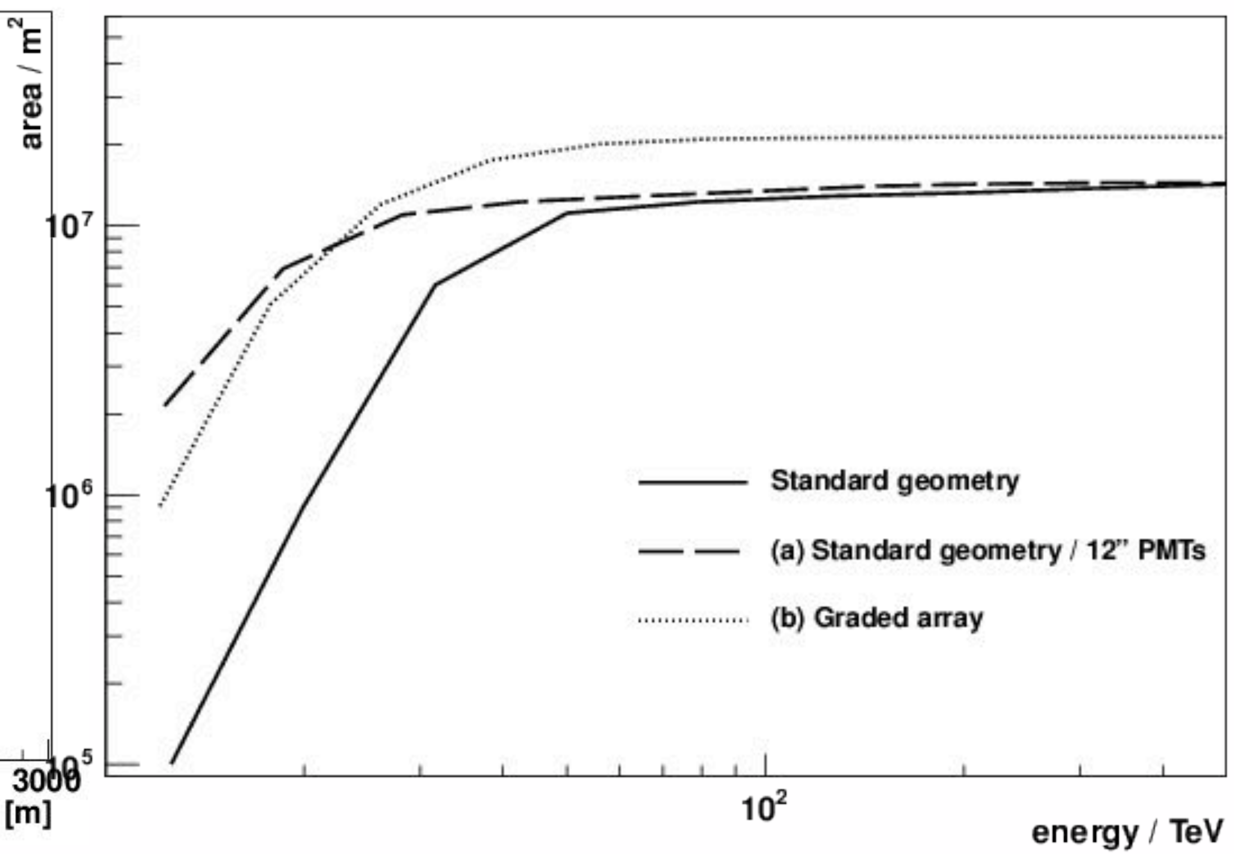


MC: 10 Hz
Data: 8 – 12 Hz

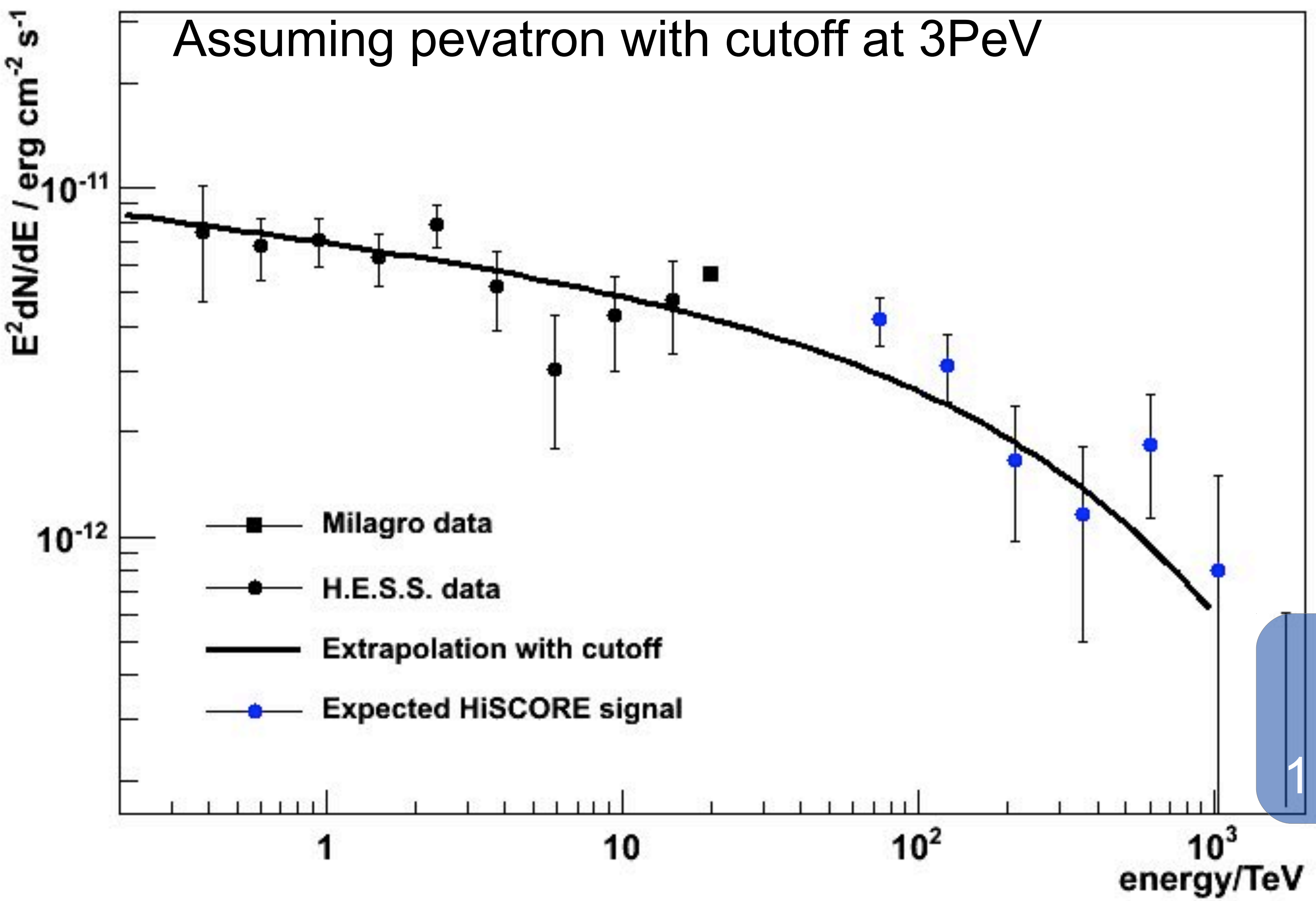
Array optimization

Simulation studies:
→ Large PMTs (12")
→ Graded array layout



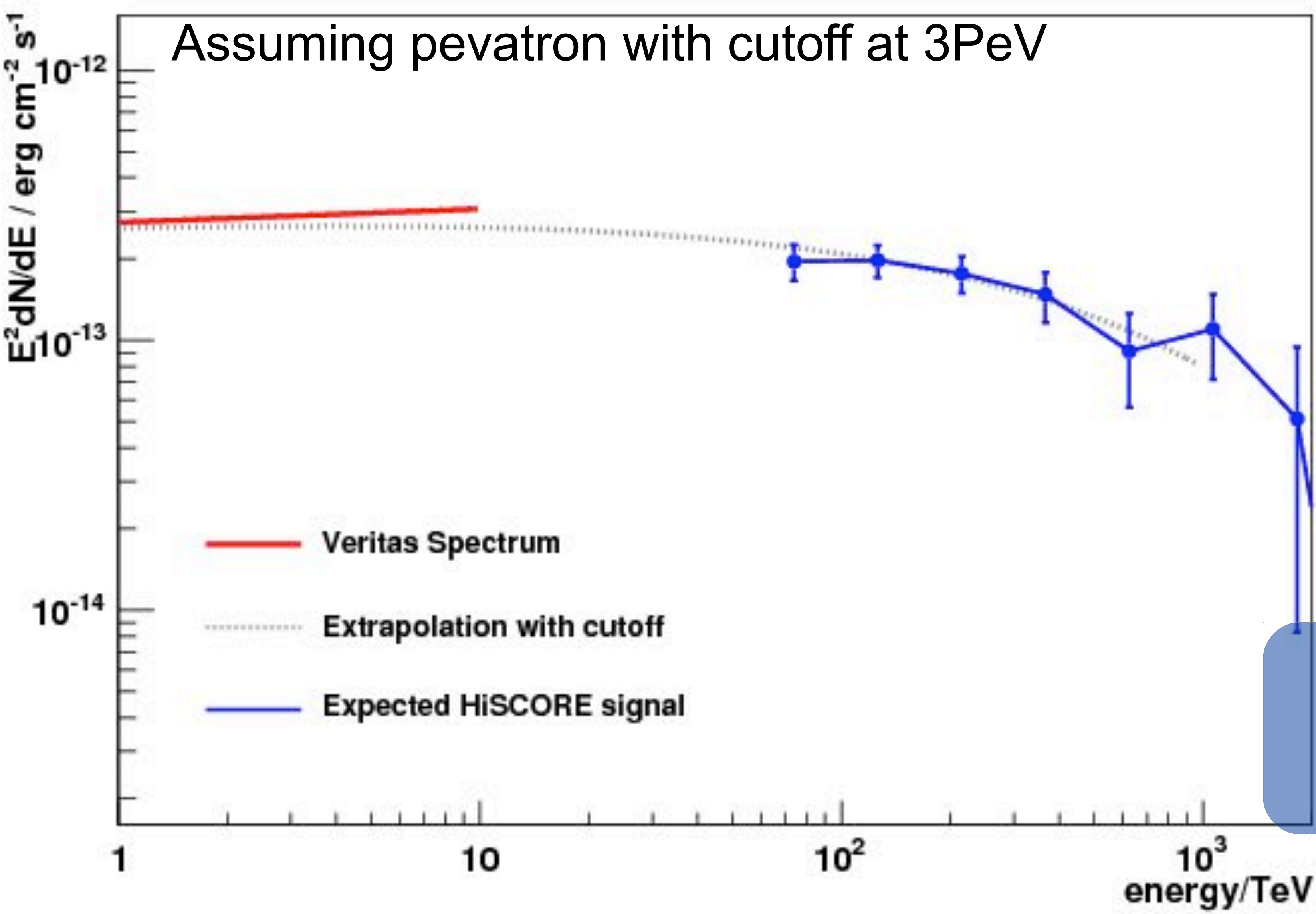


MGRO J1908+06



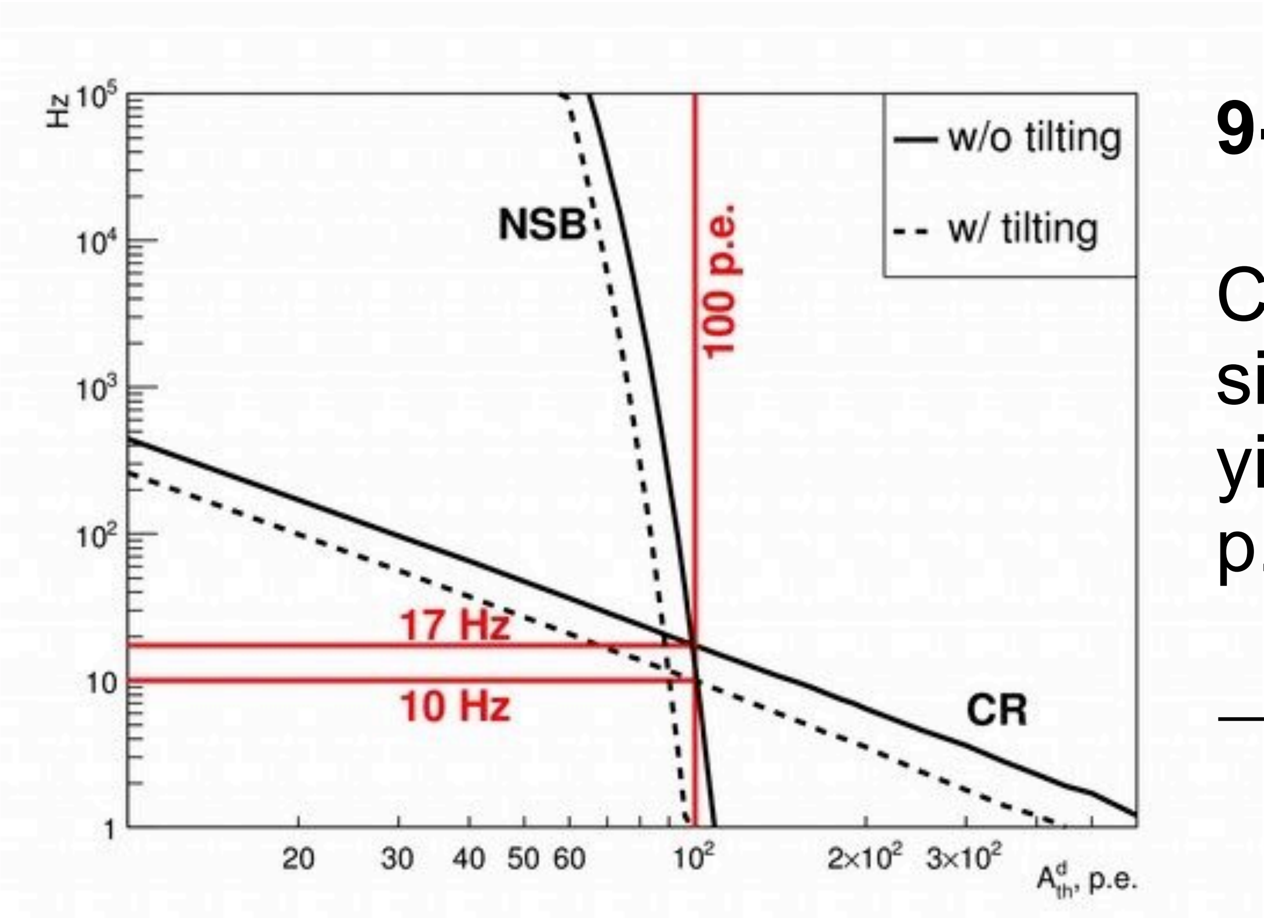
10 km²
No μ det.
1 year (200h)

Tycho Supernova remnant



100 km²
No μ det.
3 years

Single station rate and Energy threshold



9-station array:

Comparison of MC simulation with data yields a threshold of 100 p.e. at discriminator level

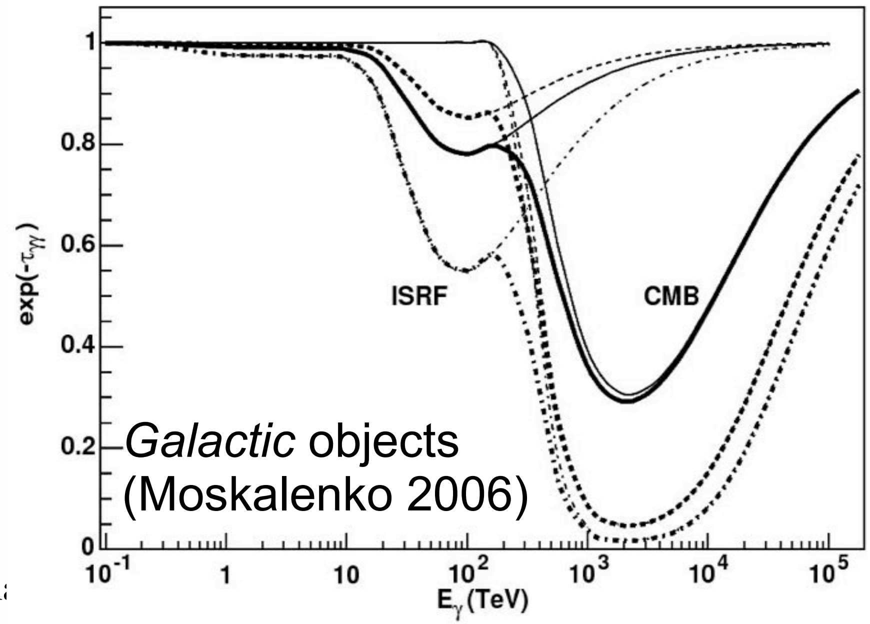
→ 180 p.e. threshold

Air Cherenkov imaging and timing

	Imaging ACTs	Timing arrays
Direction	Image orientation	Shower front arrival times
Particle type	Image shape	Lateral density function Arrival times Time width (FWHM)
Energy	Ch. photon count	Ch. photon count

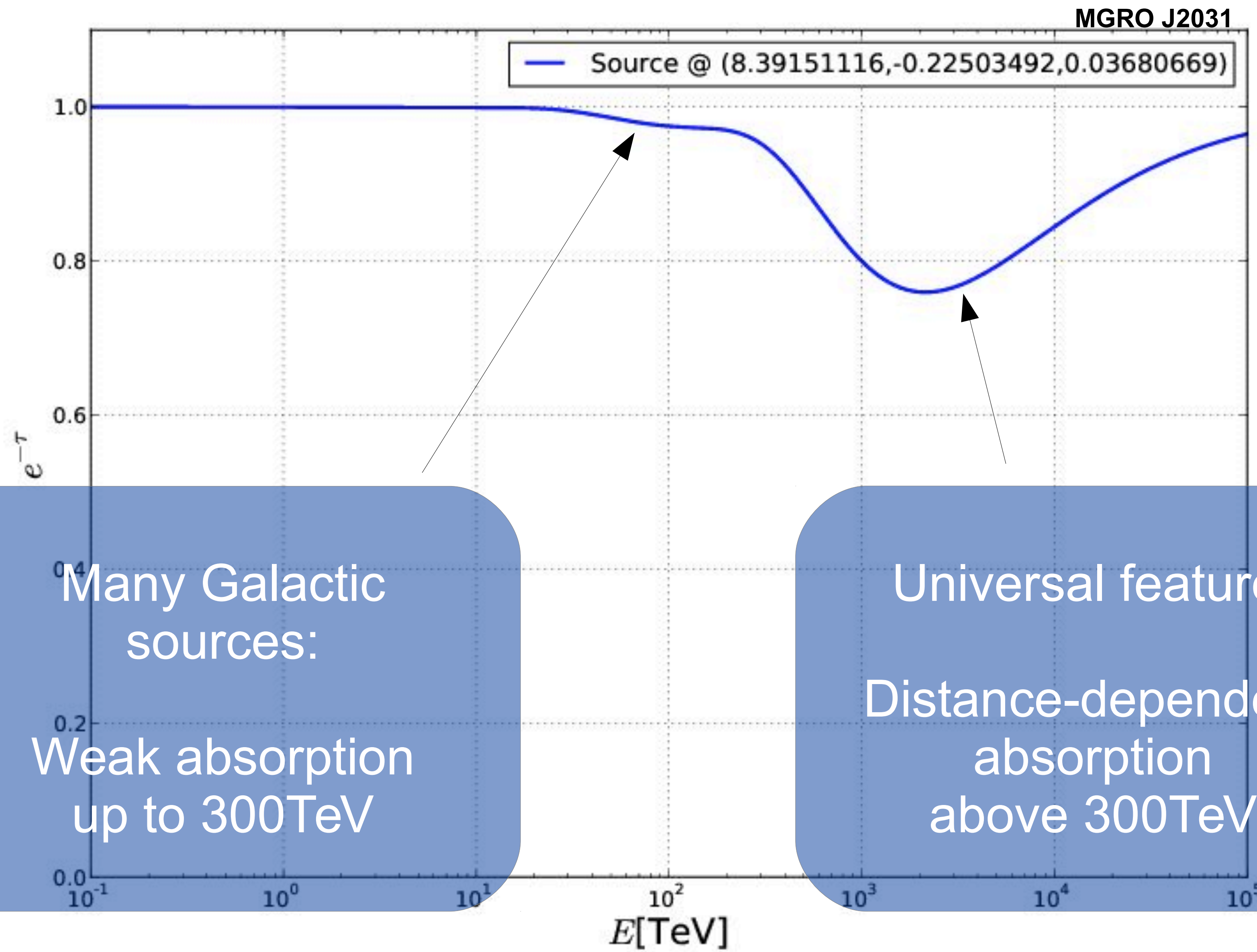
Multi-TeV to PeV Gamma rays

- Spectroscopy of cutoff regime of Galactic sources
  - Extension of known hard source spectra
  - Search for cosmic ray PeVatrons
- No hadronic/leptonic ambiguity:
  - IC: Klein-Nishina regime → steep spectra
  - Pi° decay: hard spectra possible
- Absorption e+e-:
  - 20+TeV: Mid- to far-infrared EBL *(Extragal.)*
  - 100 TeV: ISRF (*Galactic*)
  - 3 PeV: CMB (*Galactic*)



martin.tluczykont@physik.uni-h

Absorption (e^+e^-), Galactic



A. Maurer

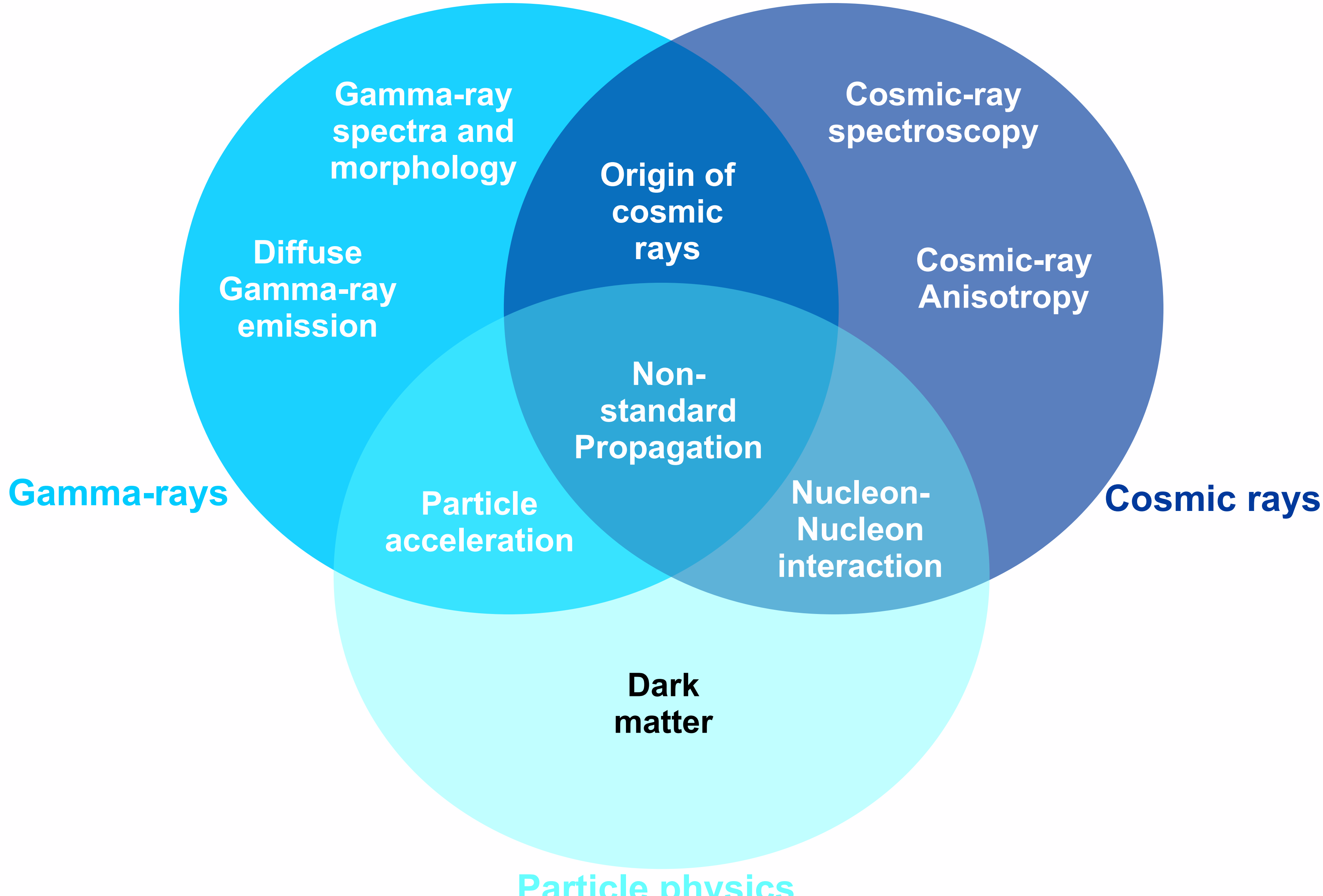
Many Galactic sources:

Weak absorption up to 300TeV

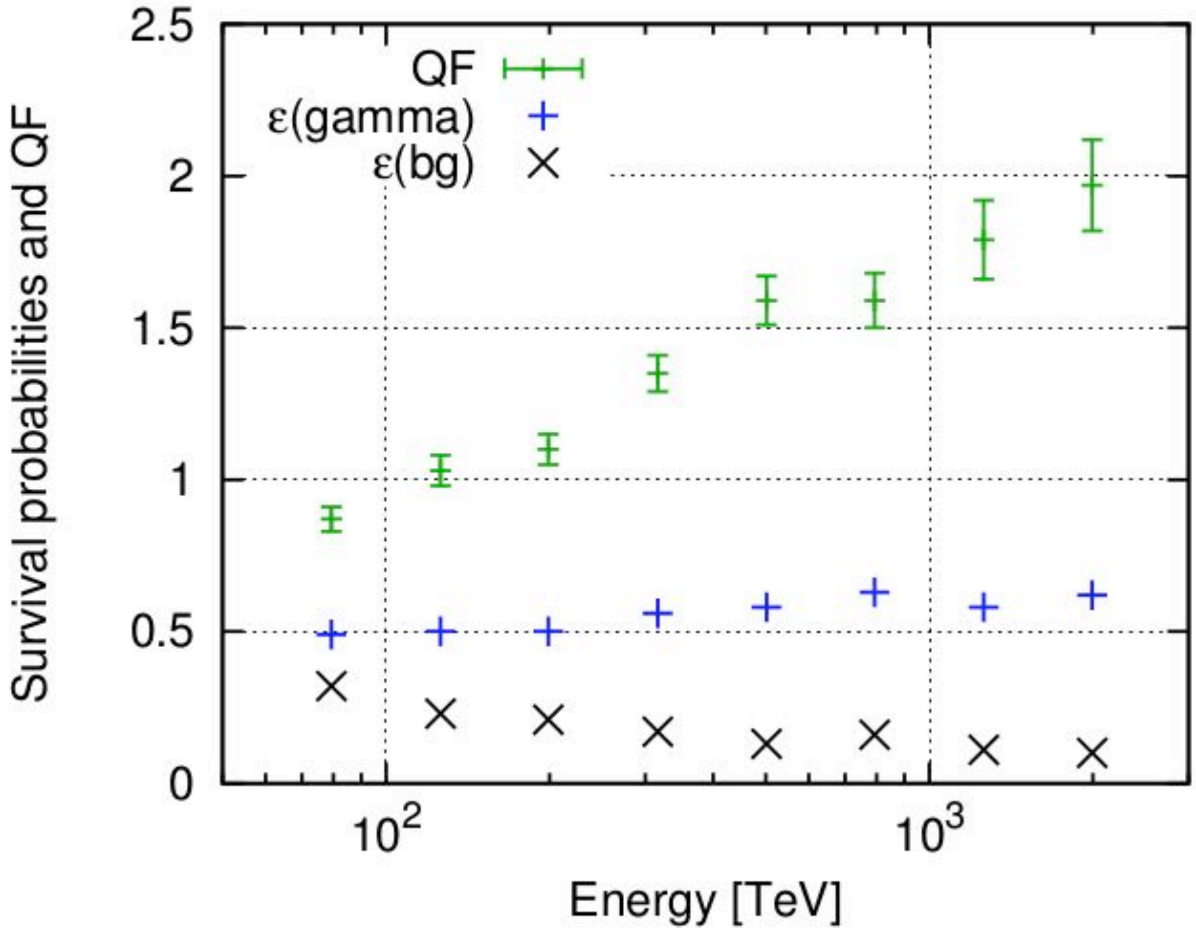
Universal feature:

Distance-dependent absorption above 300TeV

Astroparticle physics topics



Particle separation Q-factor (only timing array)



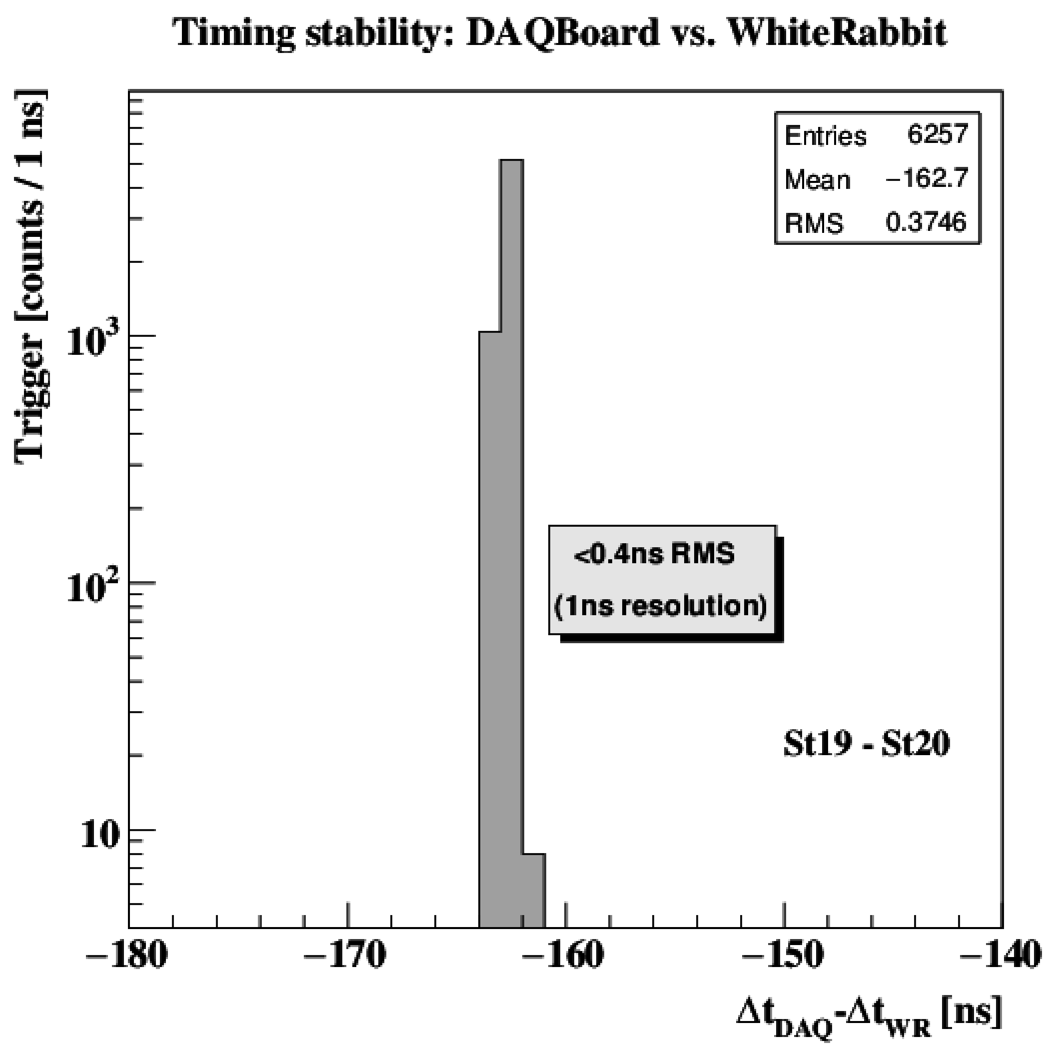
- Xmax vs. E
- Shower front rise time
- Systematic differences between Xmax reconstruction methods

Time calibration

T-cal systems yield comparable accuraccies:

Cross check of timing stability between DAQBoard and WhiteRabbit:

RMS<0.4 ns

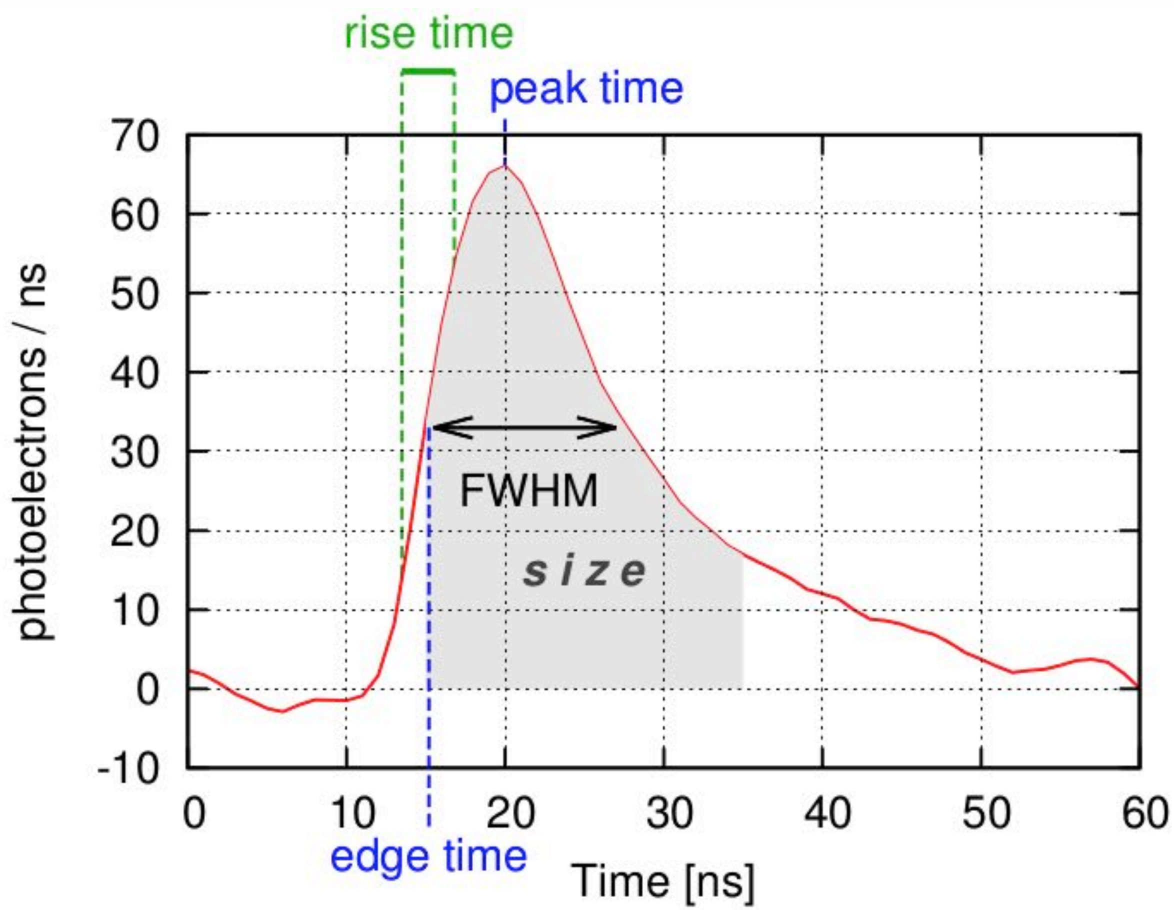


Detection methods for gamma astronomy

Method	E_{thr}	Angular resolution	ΔE/E	γ/h	Duty cycle
Particles	~3 TeV Water: 100 GeV	~1° <0.5°	20-50% 30-50%	~1 ~6	100%
Air Cherenkov photons	IACTs: 5GeV NonI: 10 TeV	0.1-0.2°	10-15%	~6 ~1.5-2	10%
Fluoresc.	10^{17} eV	>1°	10-15%	?	10%
Radio	10^{17} eV	<1°	10-15%	?	100%

Timing of air showers

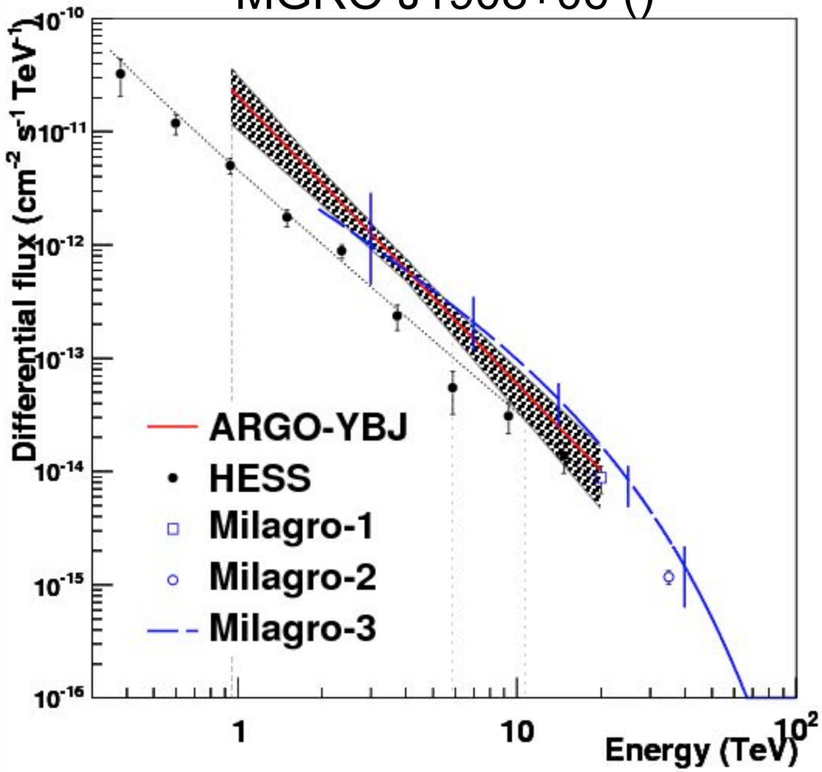
- Particle front disk width: ~30ns @ 100 m
- Cherenkov light front: disk width: <10 ns @ 100 m

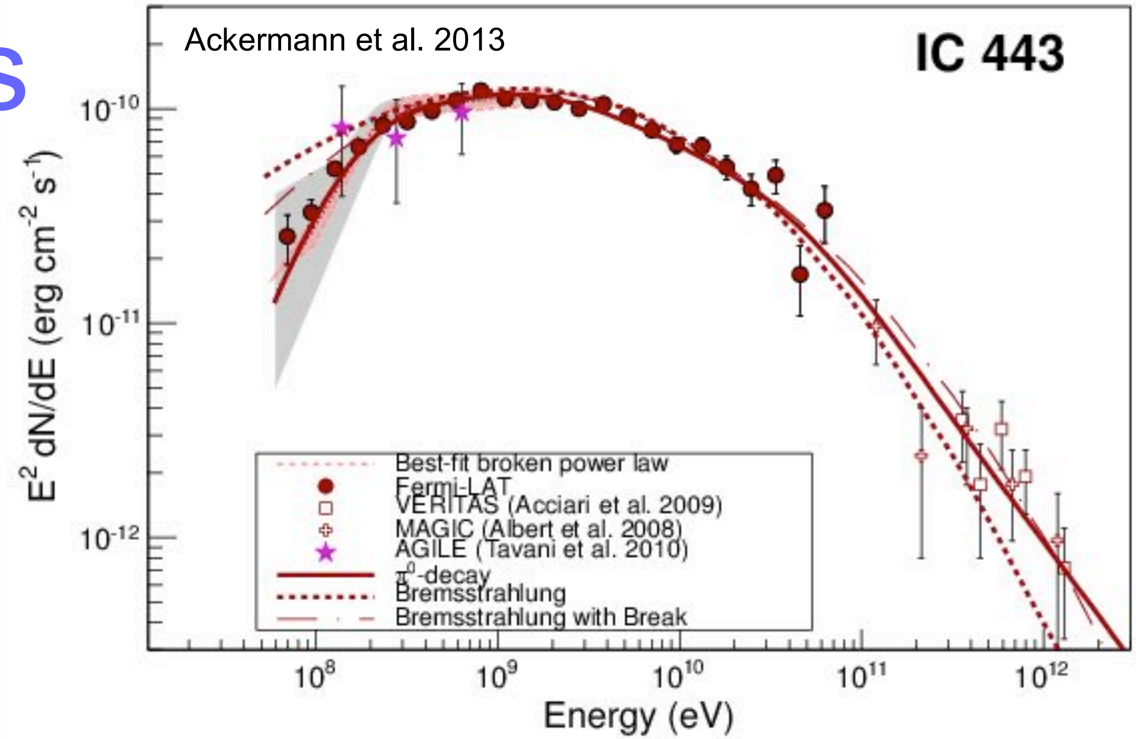


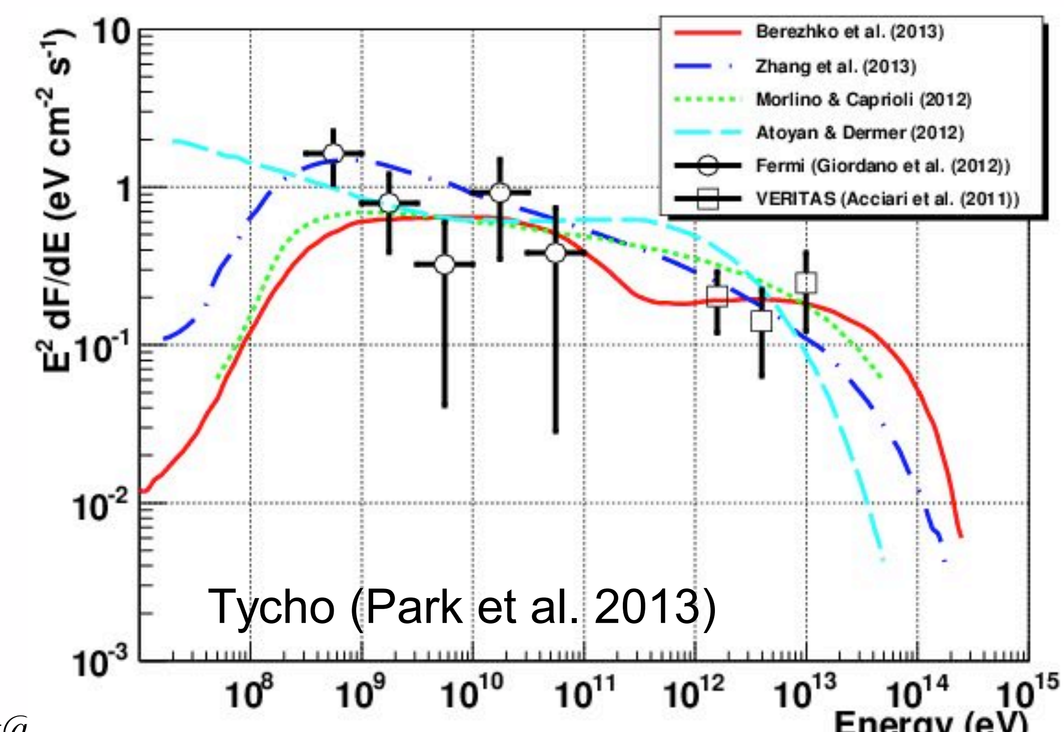
500 TeV
200 m

Galactic Gammas beyond 10 TeV

MGRO J1908+06 ()



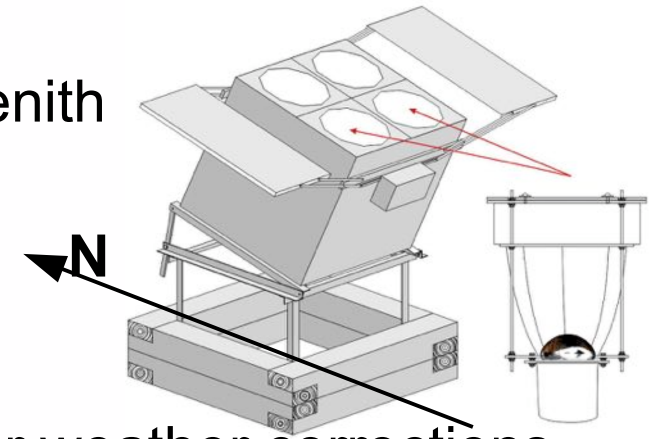




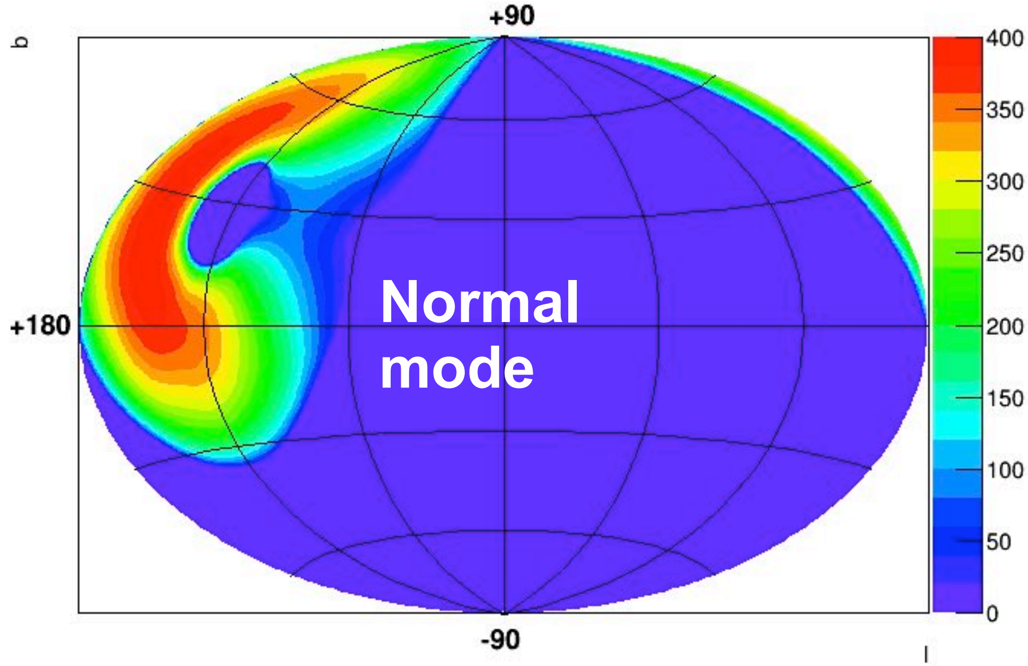
Sky coverage

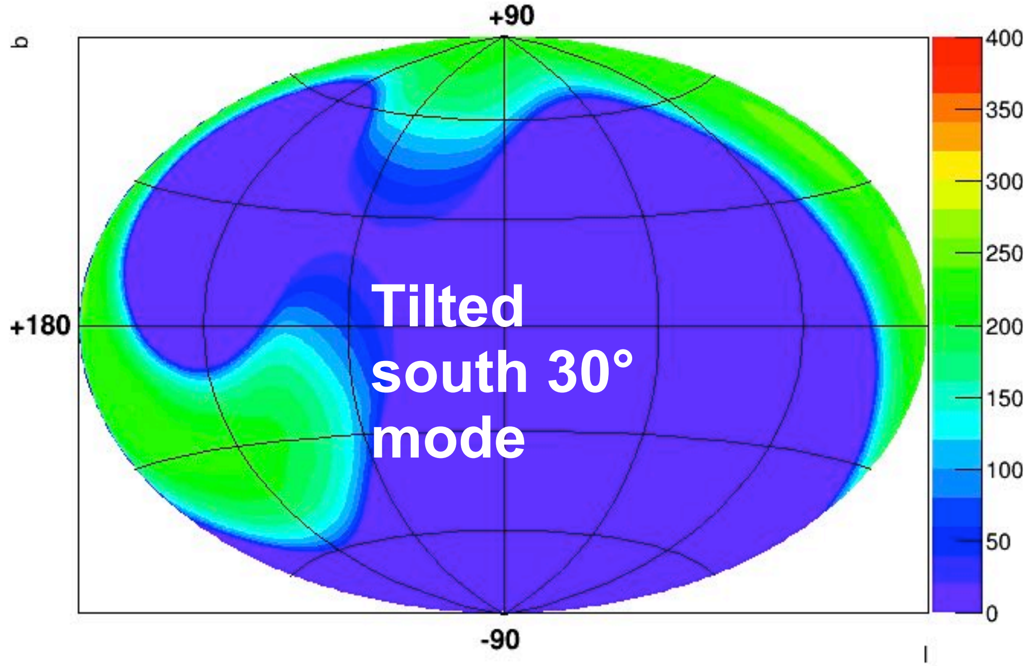
Standard observation mode: station points to zenith
Tilted mode: inclined along the north-south axis.

Tilting: coverage of different parts of the sky.

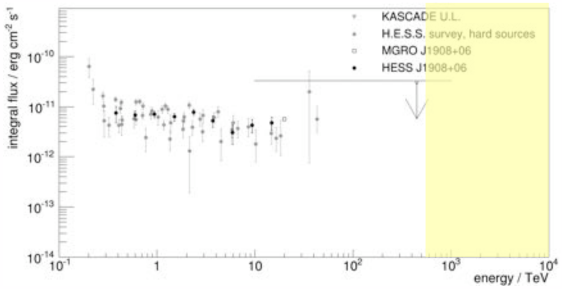


Tilted south mode: 110 h on the Crab Nebula, after weather corrections.



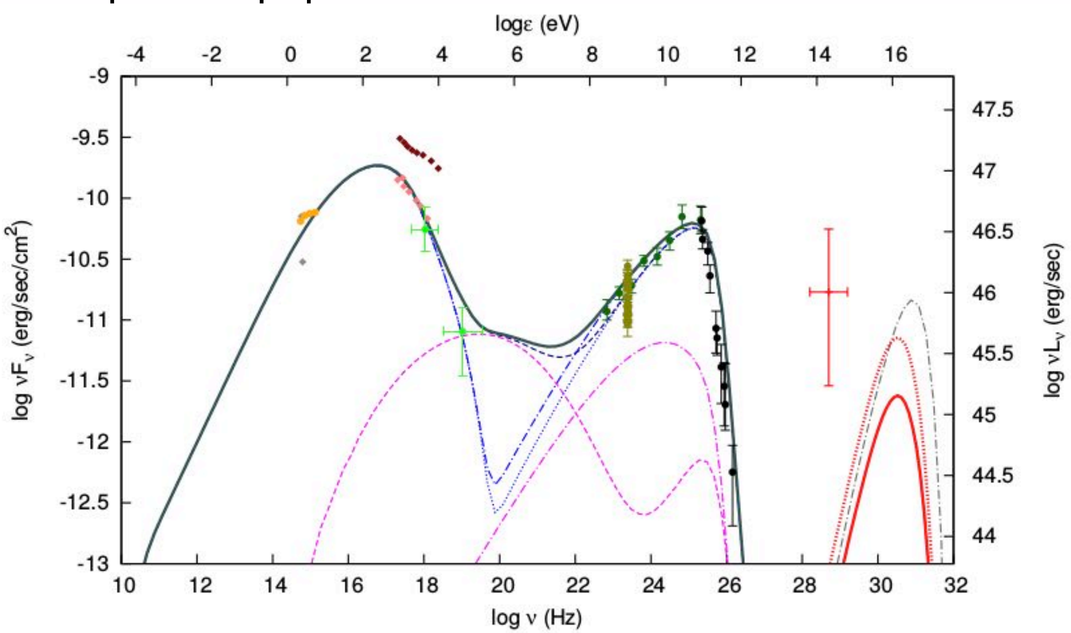


Extragalactic UHE gamma-rays

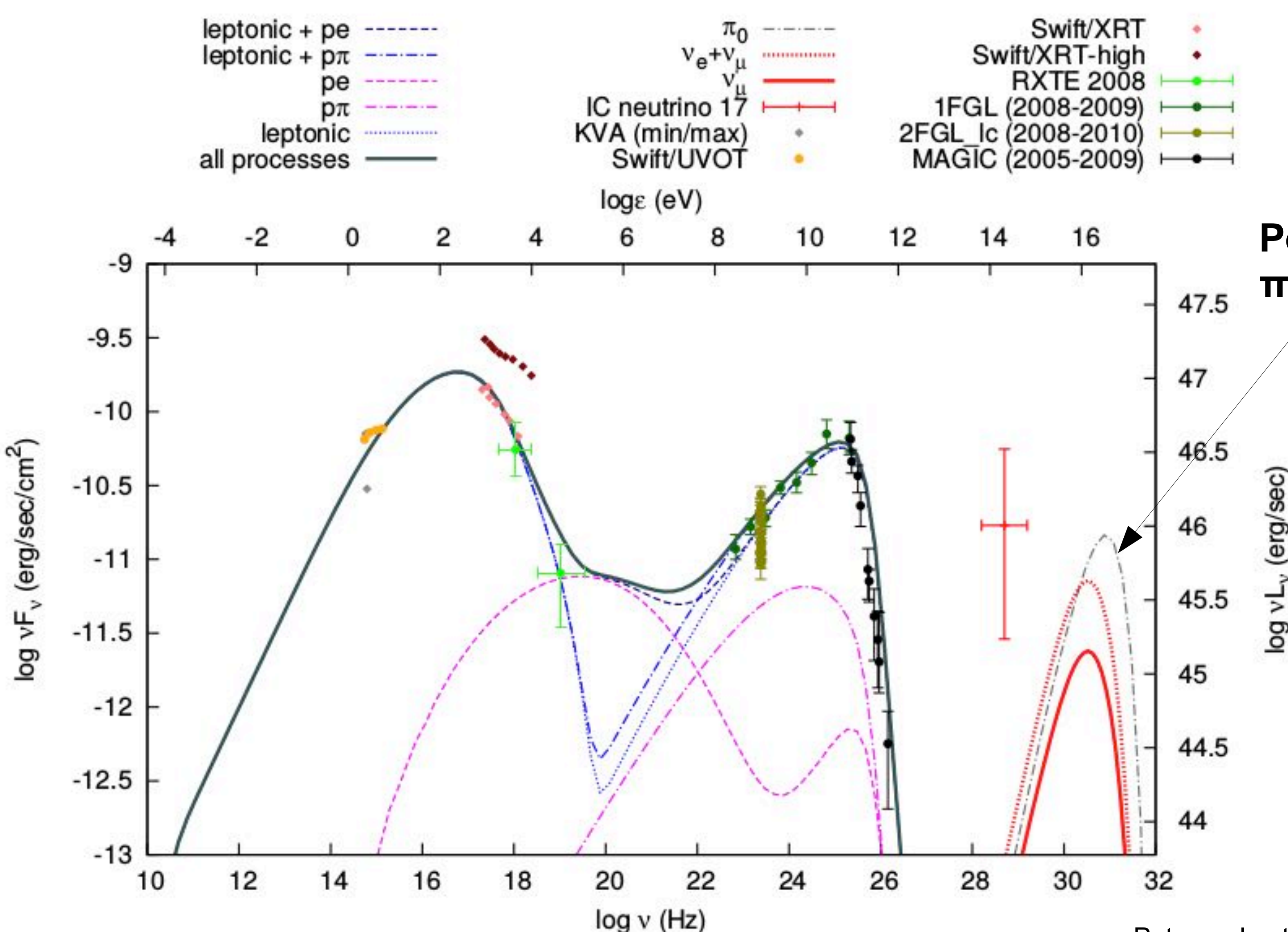


- **The IceCube signal (Aartsen et al. 2013, 2014)**
  - 1st 3 years of full IceCube data: 37 UHE neutrinos (30 TeV – 2 PeV)
  - Presence of astrophysical component favoured (5 σ).
  - Identification of 8 BL Lac objects as likely neutrino event counterparts (Padovani&Resconi 2014)

- **Lepto-hadronic emission model (Petropoulo et al. 2015)**
  - blob + B-field with Doppler factor δ, isotropic proton and electorn injection
    interaction with B-field and secondaries → particle populations:
  - protons
    - synchrotron radiation
    - Bethe-Heitler (pe) pair production
    - photopion (pπ) interactions
  - electrons and positrons
    - synchrotron radiation
    - inverse Compton scattering
  - photons
  - (+ neutrons, neutrinos)



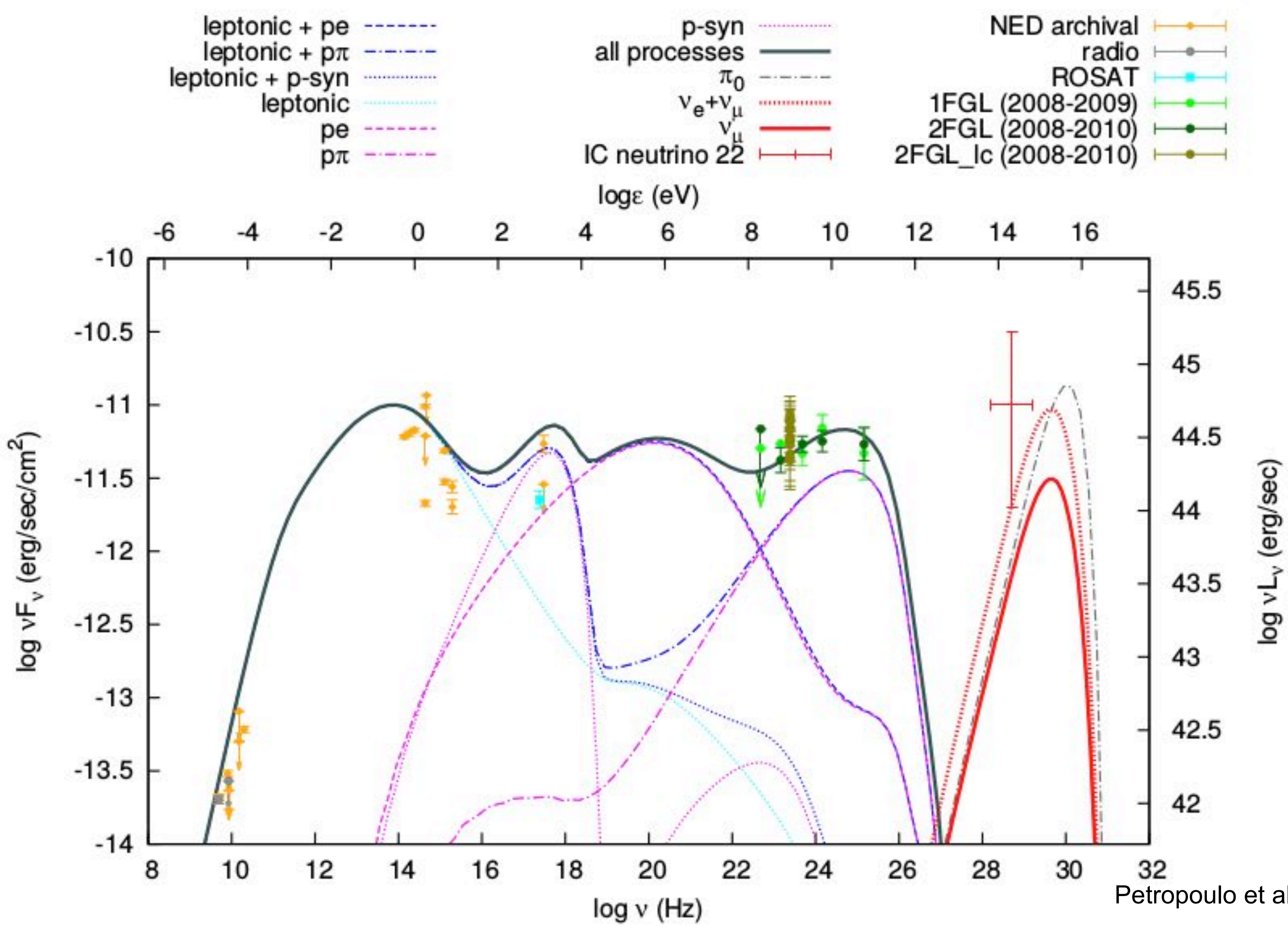
PG 1553+113 (z = 0.4)



PeV
π⁰ hump

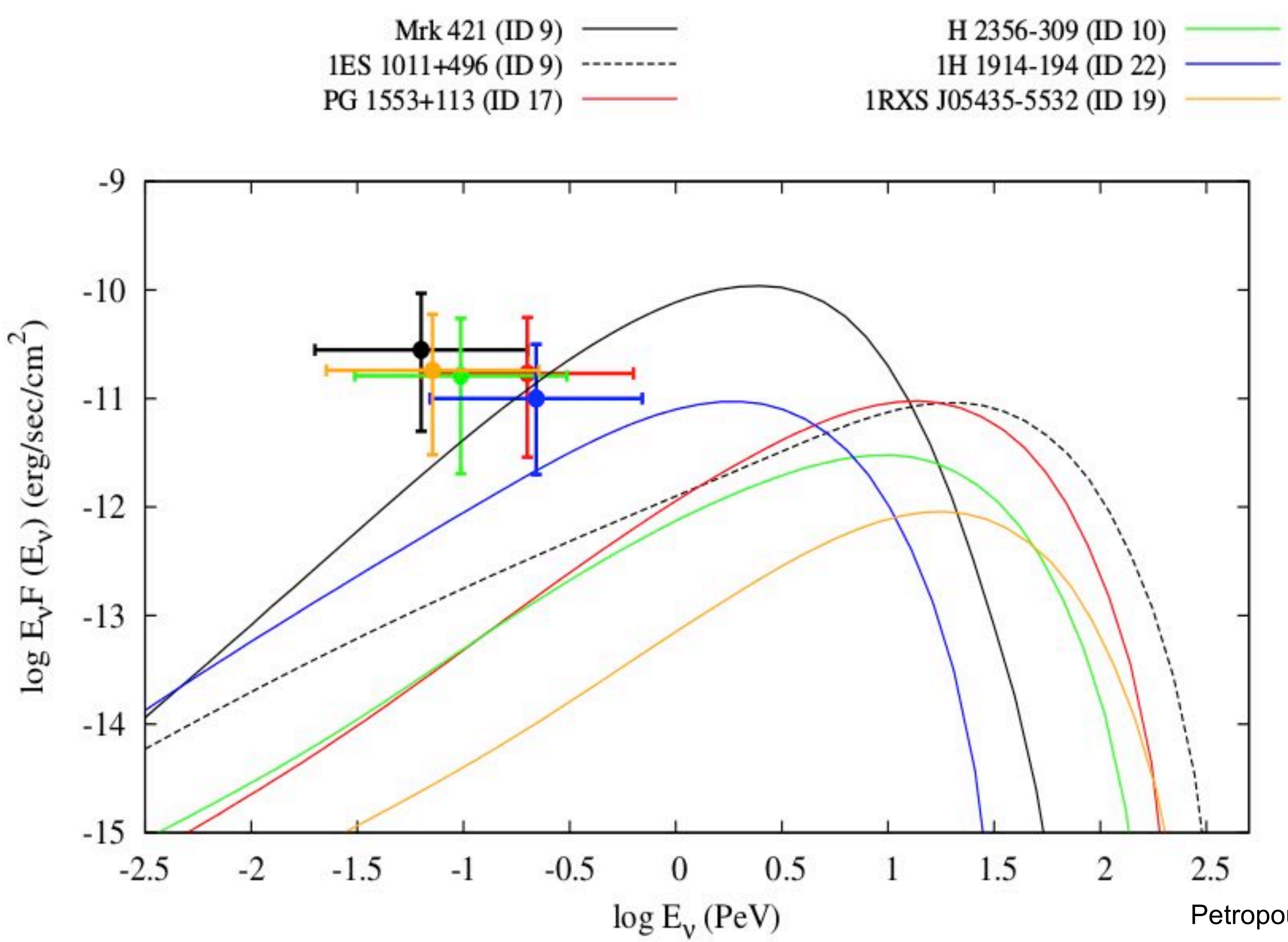
Petropoulo et al. 2015

H 1914-194 (z=0.137)



Petropoulo et al. 2015

π^0 hump and neutrino event fluxes



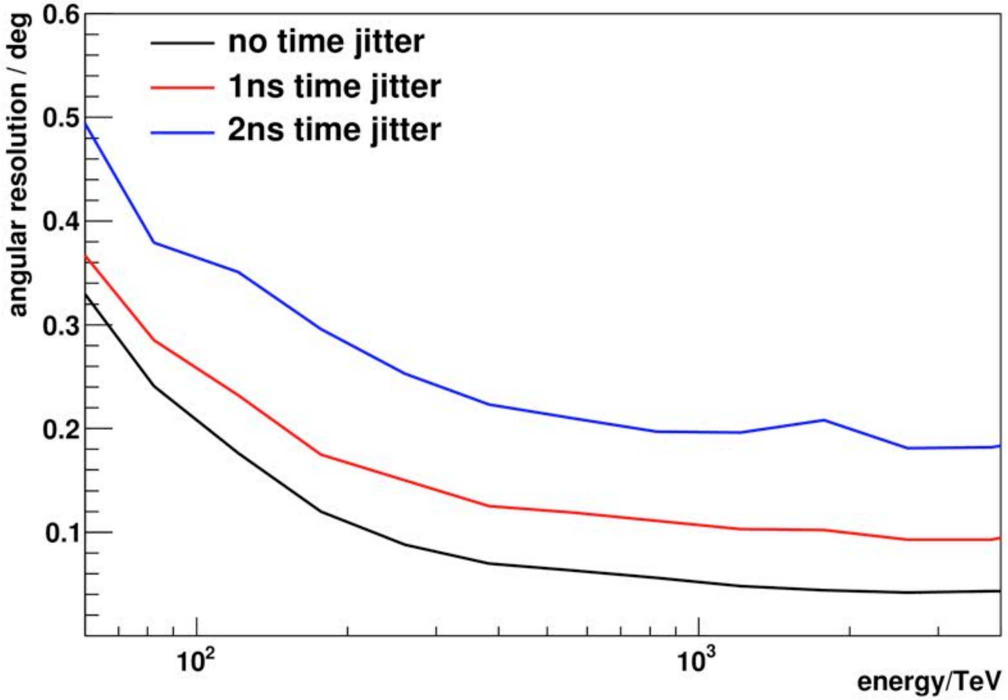
Petropoulo et al. 2015

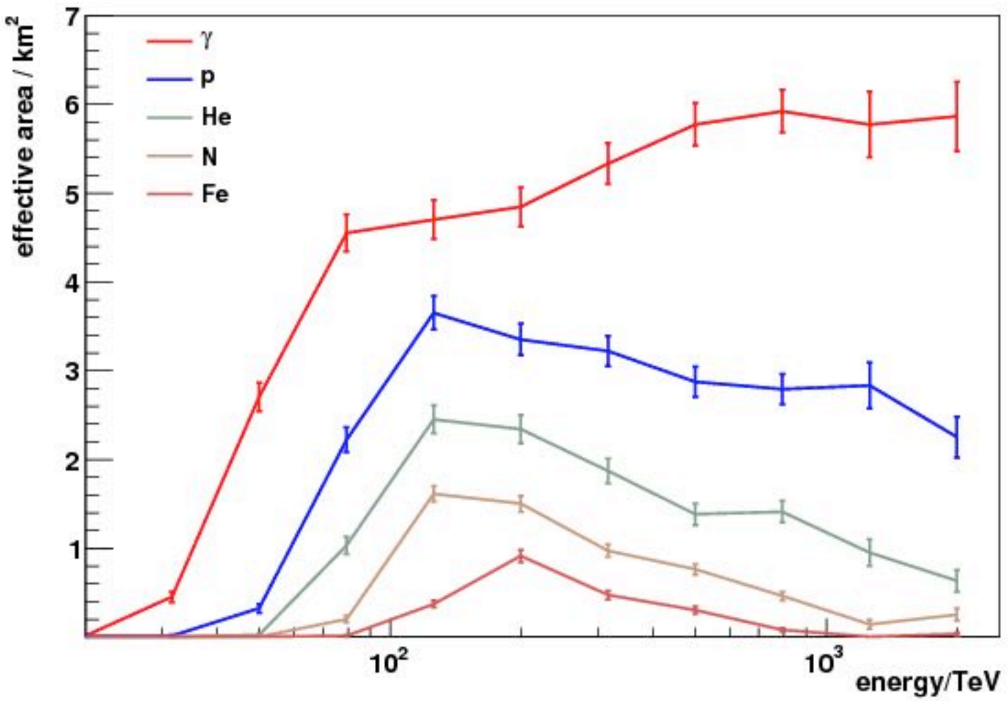
Reconstruction

Direction: photon arrival time model

Energy: Value of LDF @ 220 m

Particle type: Shower depth and Signal rise-time

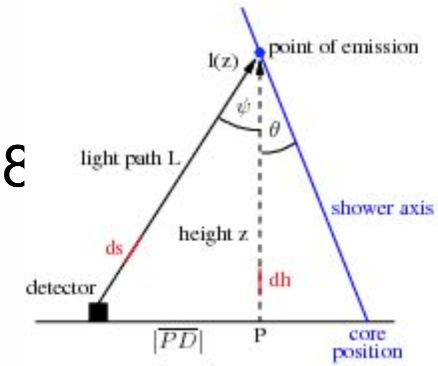




Direction reconstruction

>3 stations: model fit adapted from Stamatescu et al. 2008

Parametrization of time-delay *dt* at detector position



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

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

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

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

Slope of atmospheric refractive index

Shower height in km

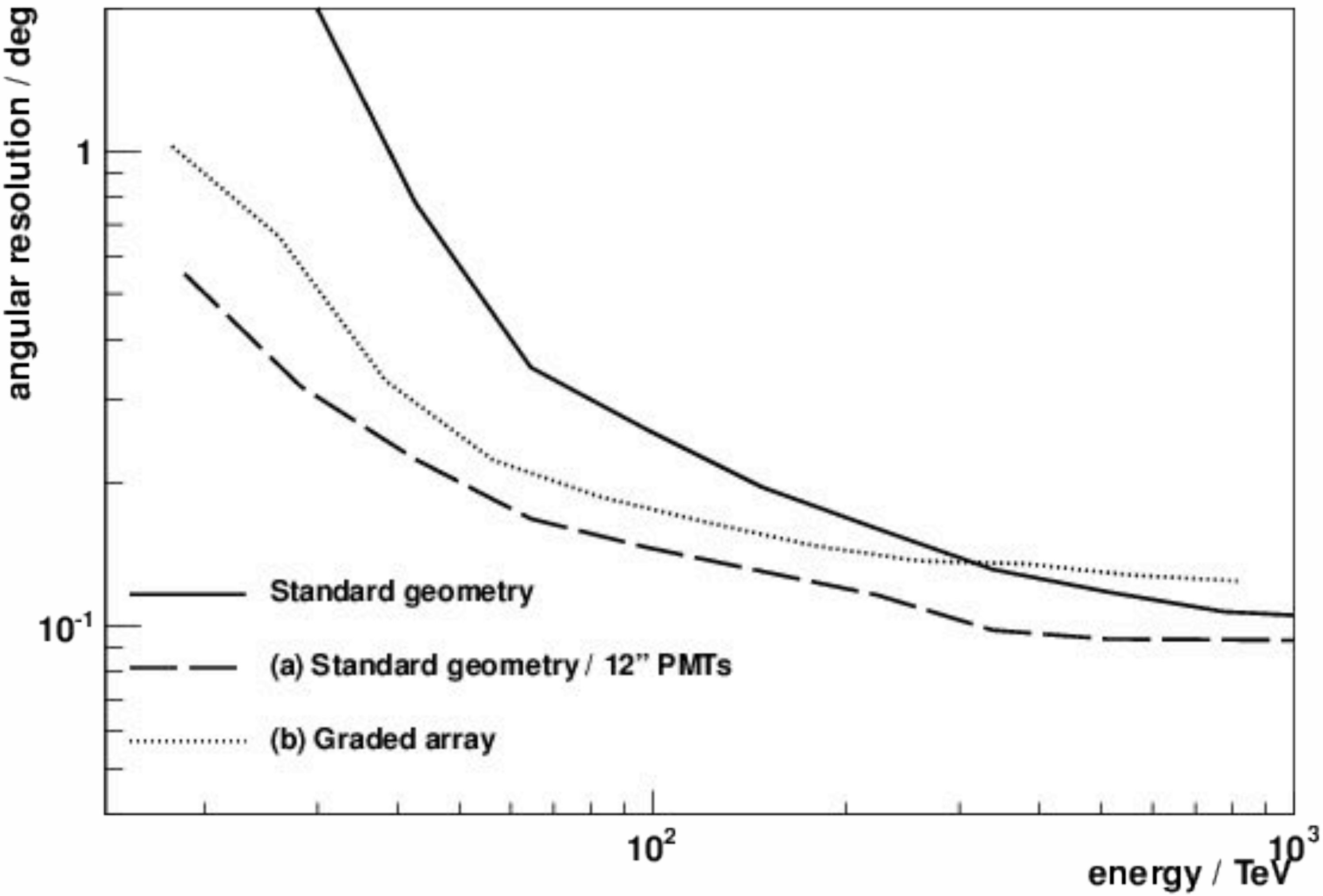
$$dt(k,z) = \frac{1}{c}\left(\sqrt{k} - \frac{z}{\cos(\theta)} + \frac{8.0}{z}\sqrt{k}\,\eta_0\left(1 - \exp\left(\frac{-z}{8.0}\right)\right)\right)$$

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

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

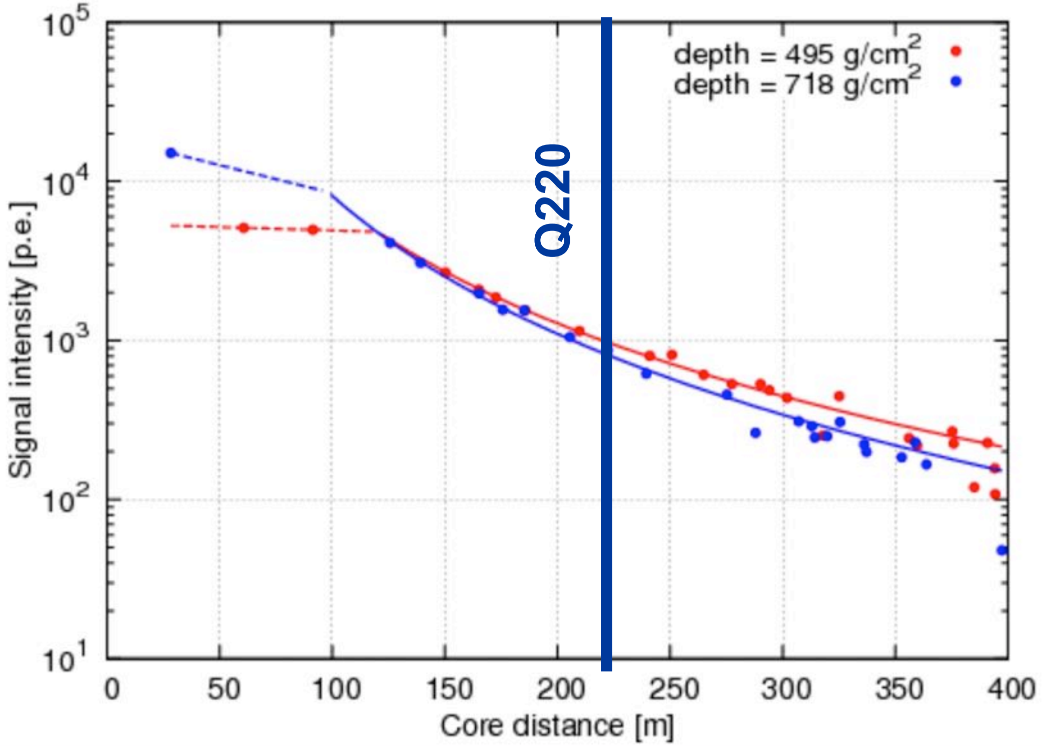
Zenith angle

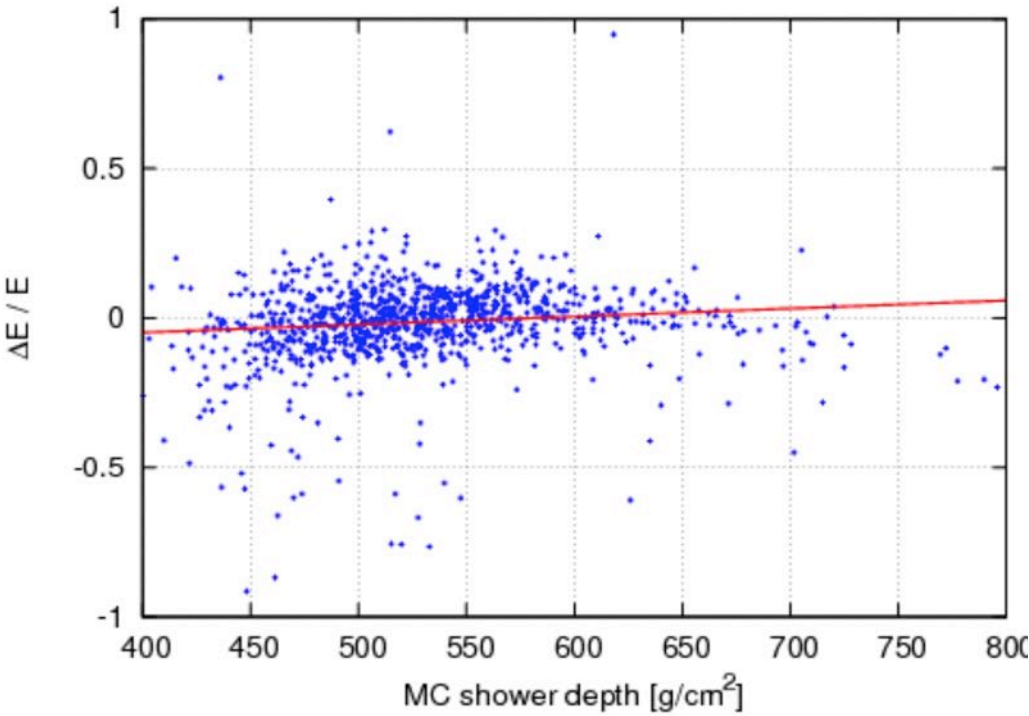
Angular resolution of alternative layouts



Energy reconstruction

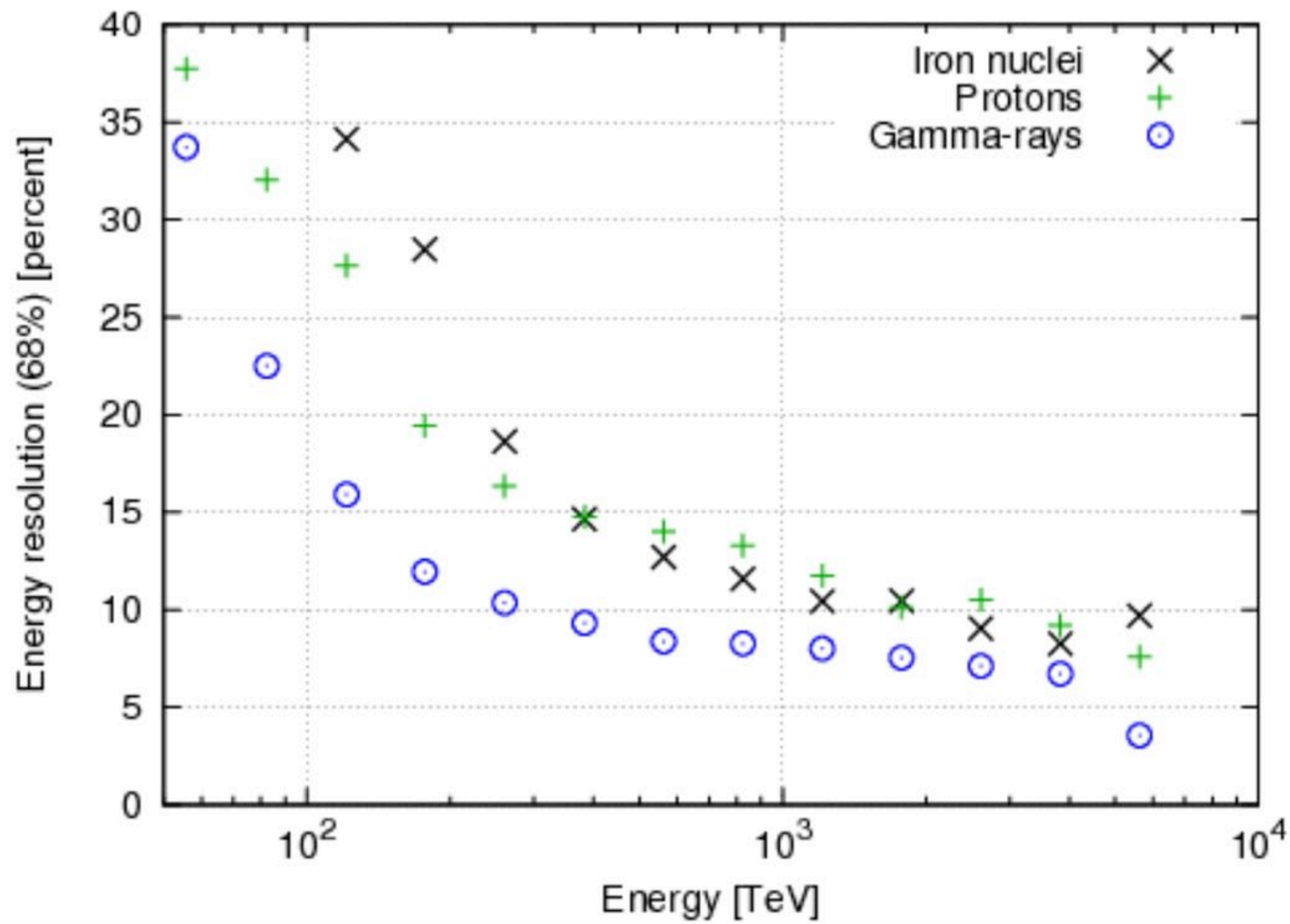
Particle energy: **Q220 = Value of LDF at 220m**





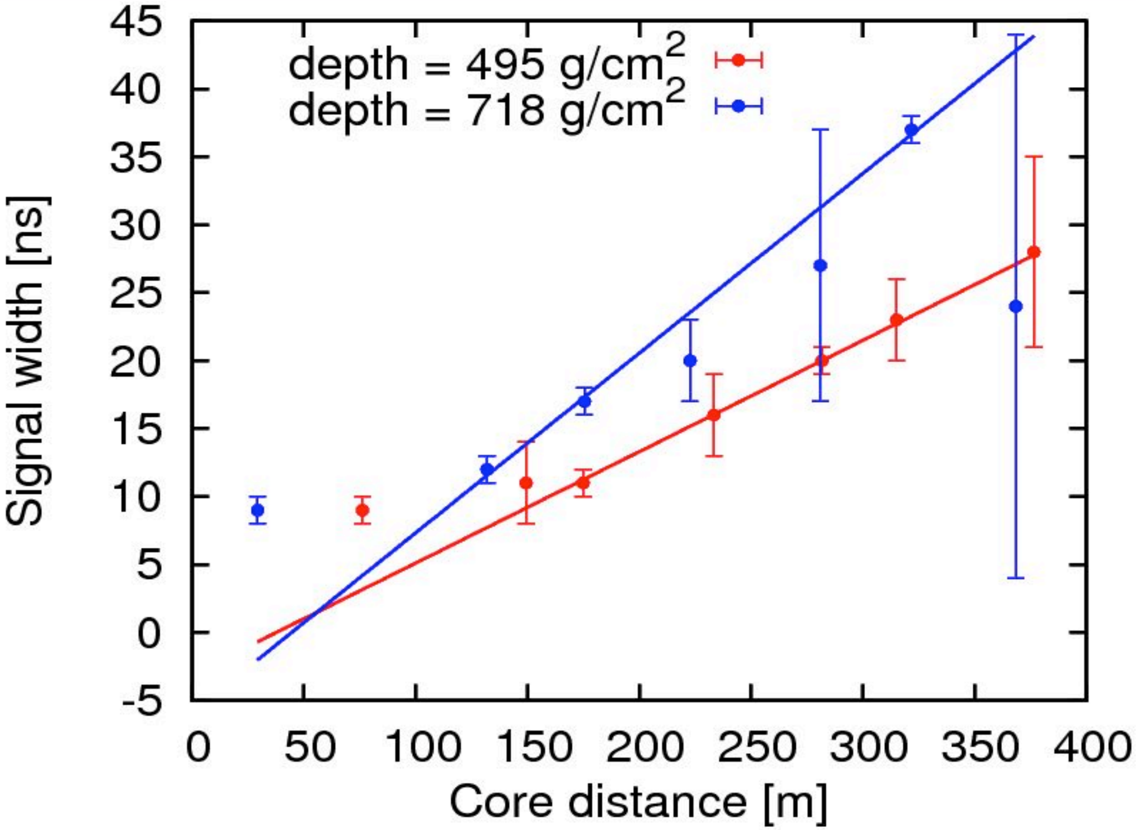
Energy reconstruction

Particle energy: **Q220 = Value of LDF at 220m**



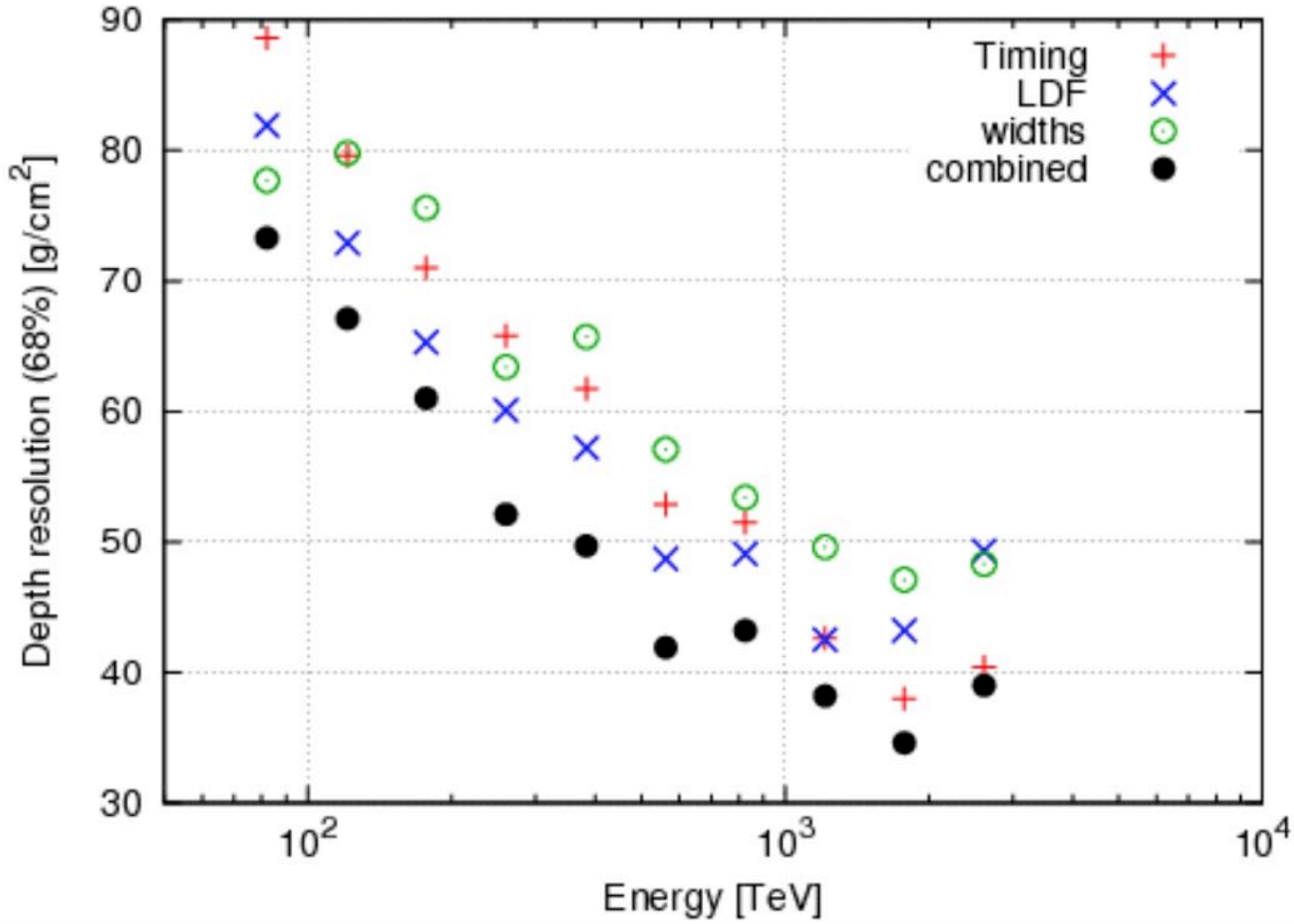
Shower depth reconstruction

- **Time model method:** one free parameter in arrival time model
- **LDF method:** Depth from LDF slope, Q50/Q220
- **Width method:** Depth from signal width

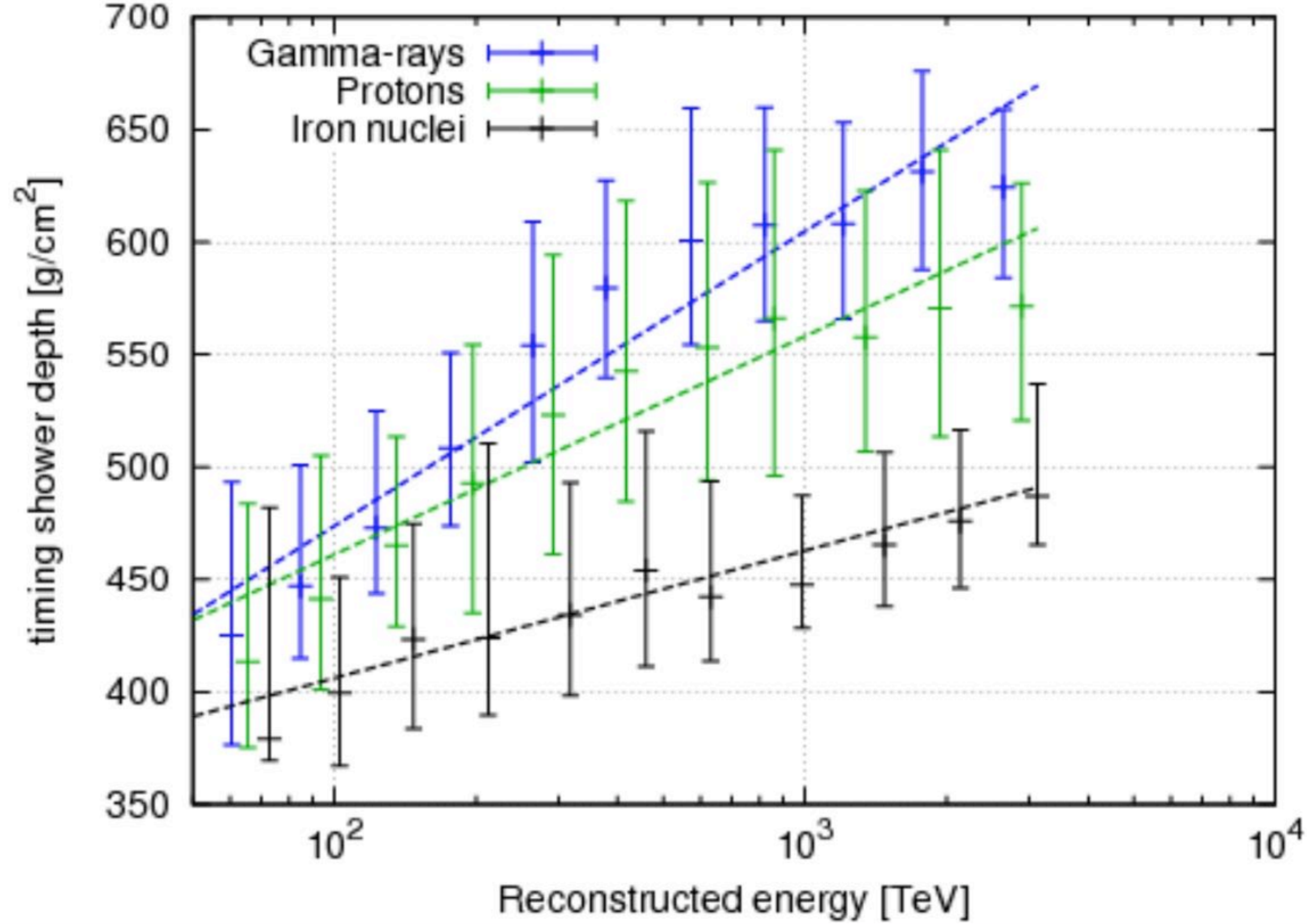


Shower depth

Depth of shower maximum

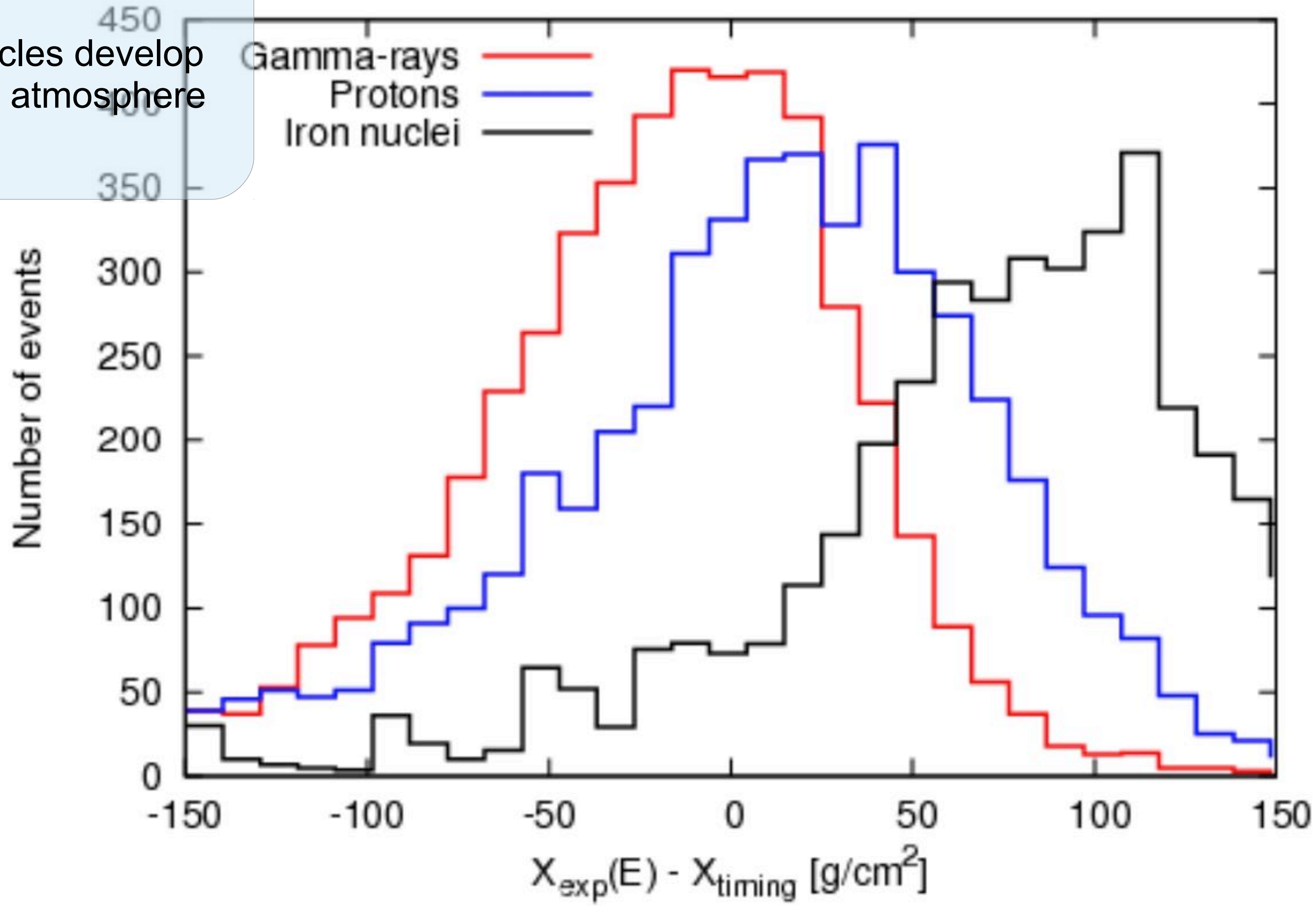


Particle separation



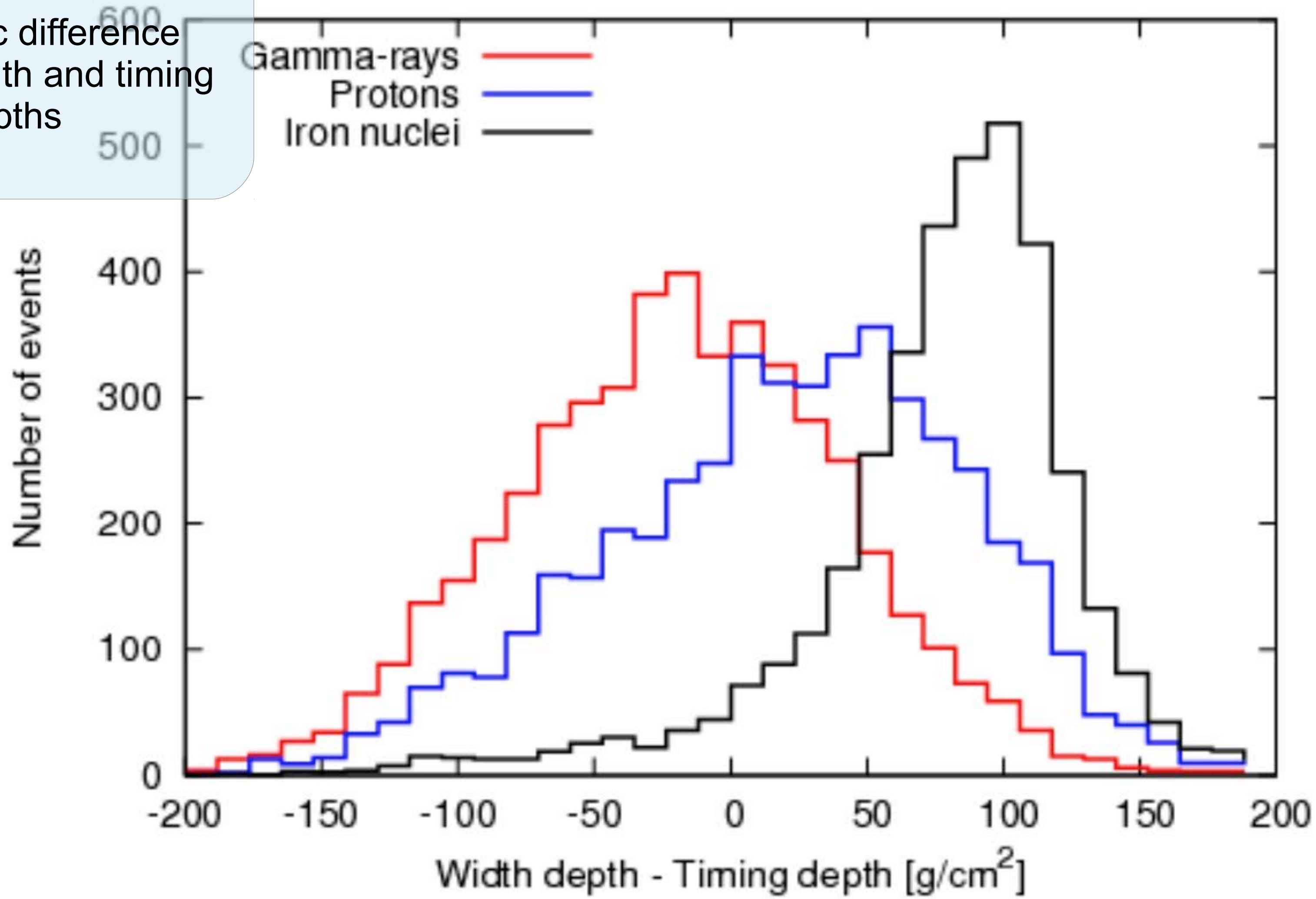
Particle separation (1)

Lighter particles develop
Higher up in atmosphere

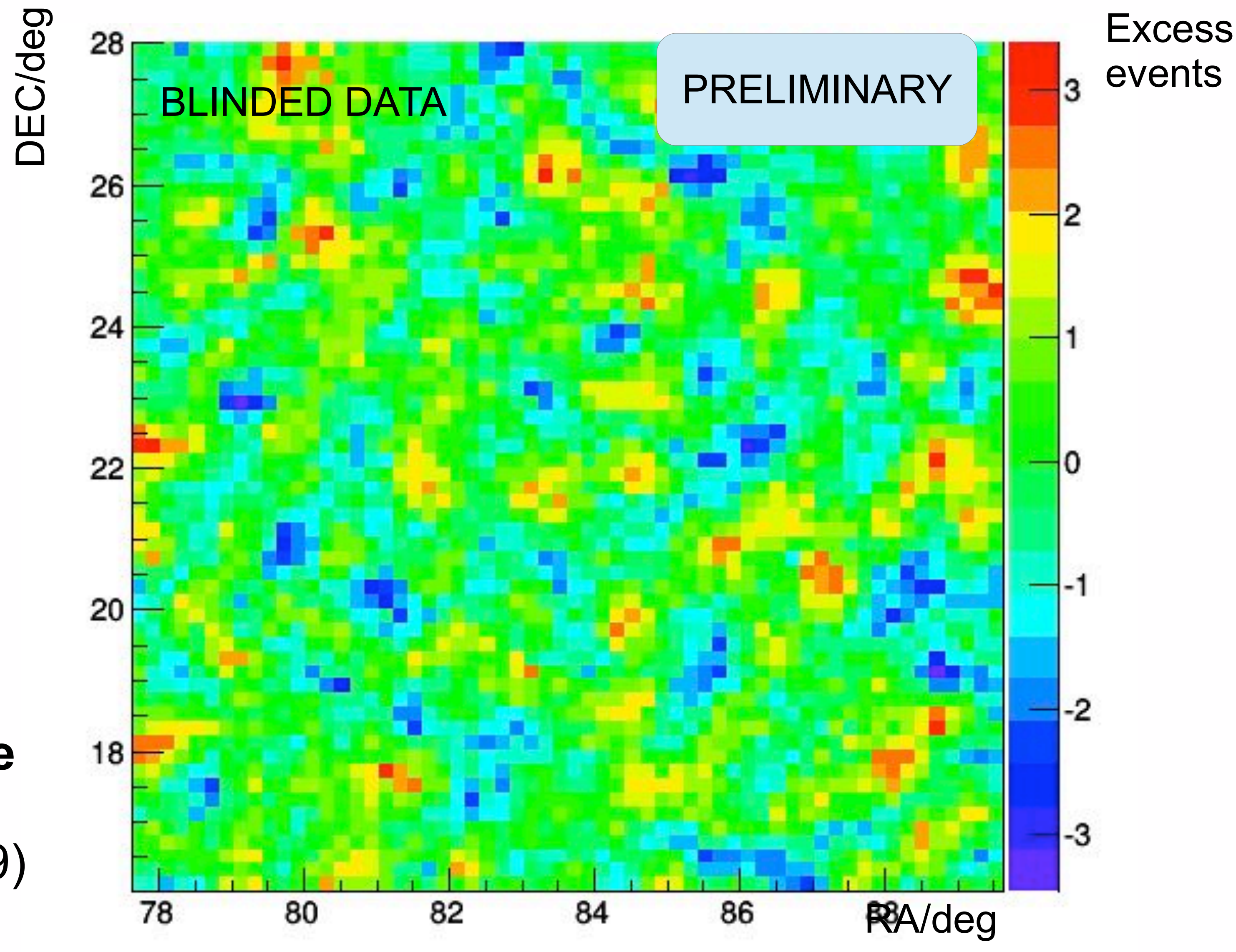


Particle separation (2)

Systematic difference
Between width and timing
Depths



Background for pointsource search



Significance map
(Li&Ma Eq. 9)