Towards Gamma-ray astronomy with timing-arrays

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ECRS 2014, Kiel

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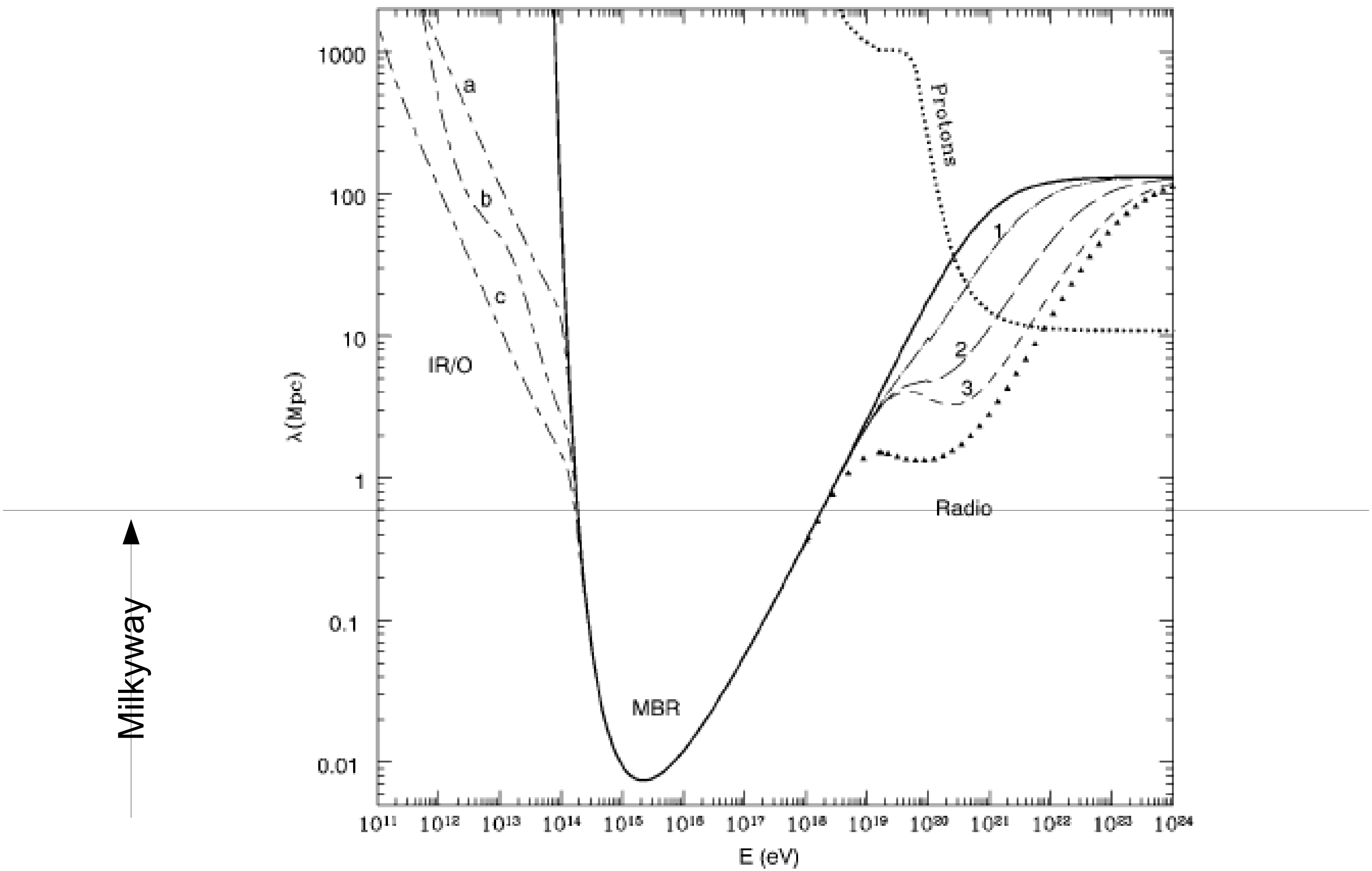
Gamma-ray astronomy



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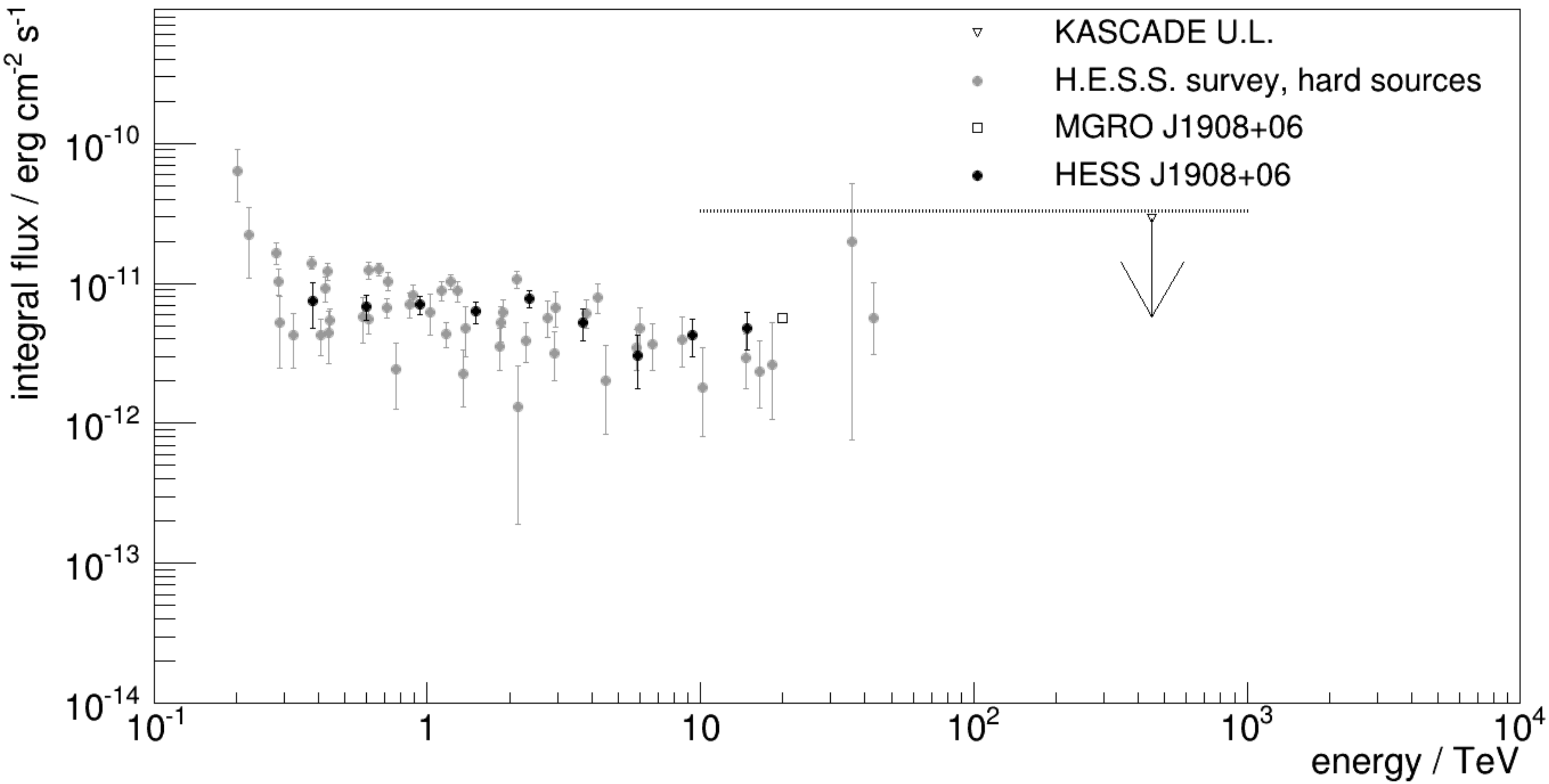
Gamma-ray astronomy



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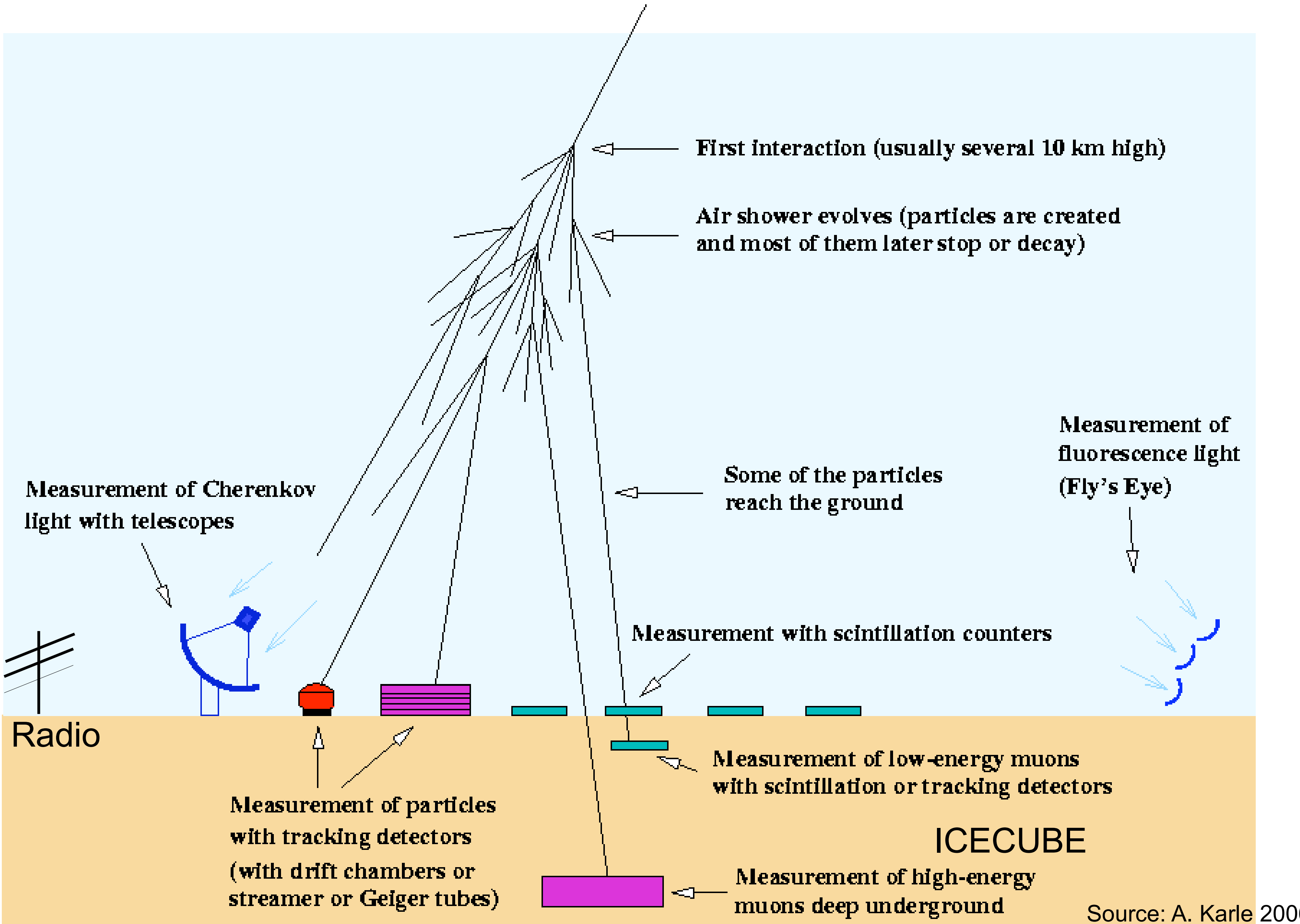
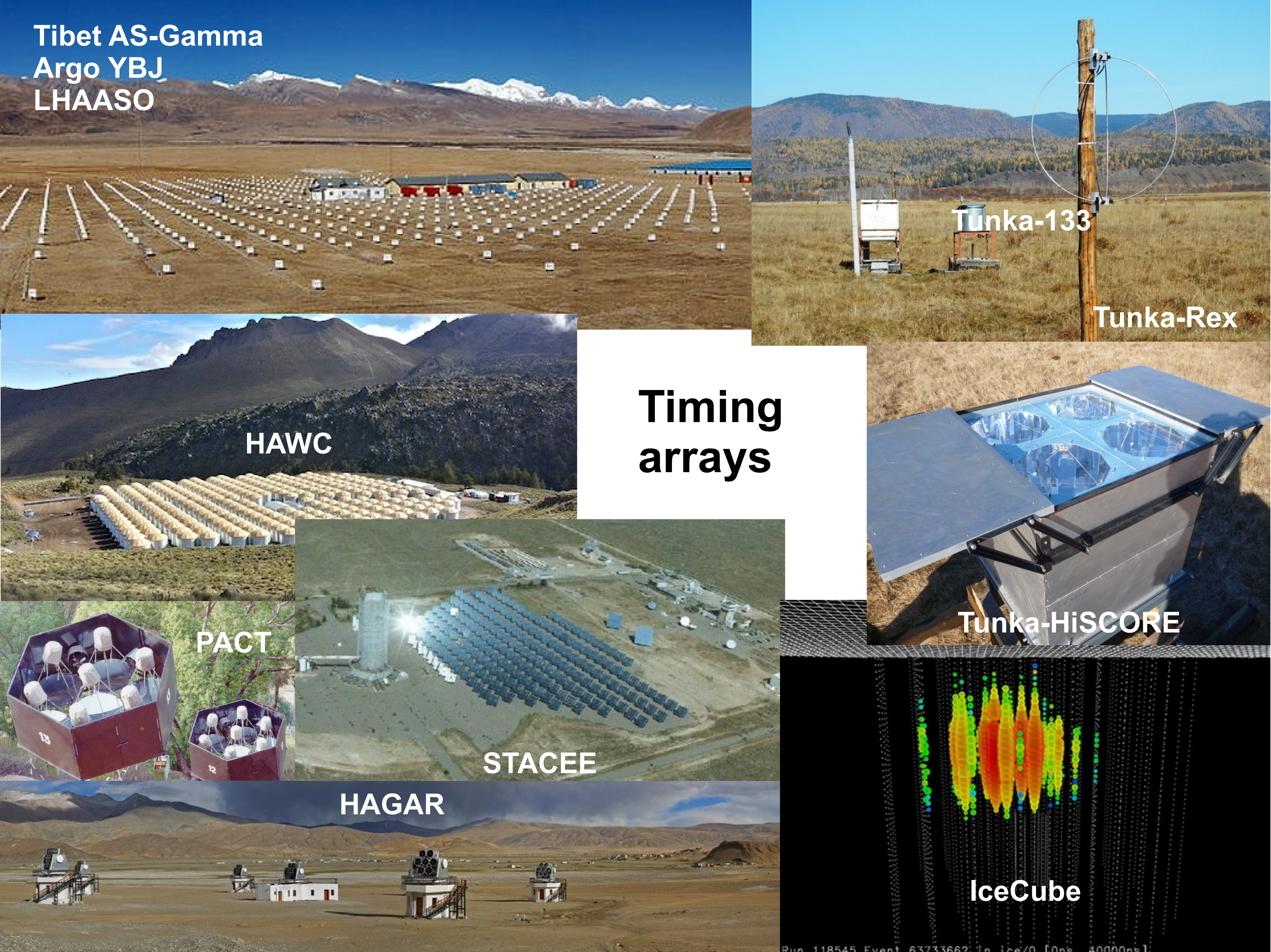
Measuring cosmic-ray and gamma-ray air showers




Tibet AS-Gamma
Argo YBJ
LHAASO
Tunka-133
Tunka-Rex
Timing arrays
HAWC
Tunka-HiSCORE
PACT
STACEE
HAGAR
IceCube

Timing arrays and 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°	30-50%	~1 ~6	100%
Cherenkov	IACTs: 5GeV NonI: 10 TeV	0.1-0.2°	10-15%	~4 ~1.5-2	10%
Fluoresc.	10^{17} eV	>1°	10-15%	?	10%
Radio	10^{17} eV	>1°	10-15%	?	100%

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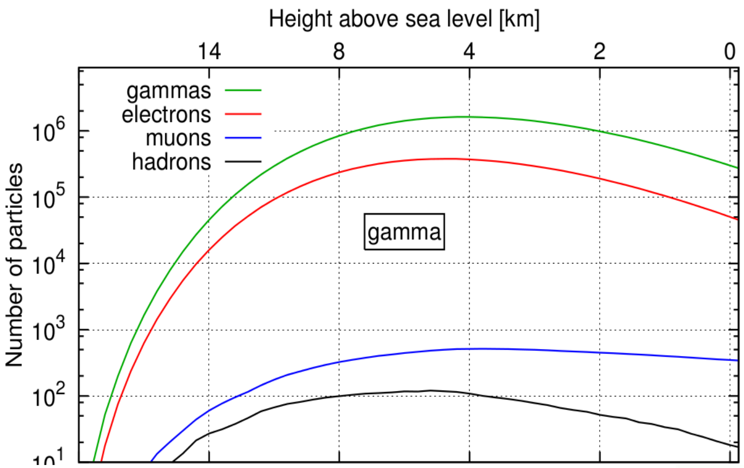

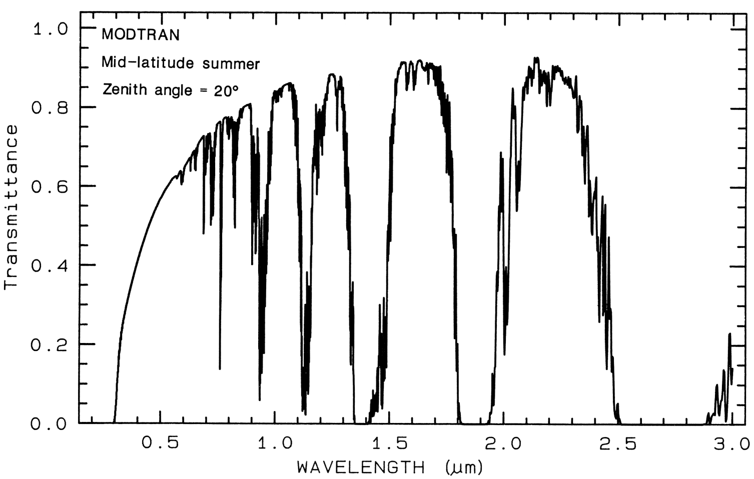

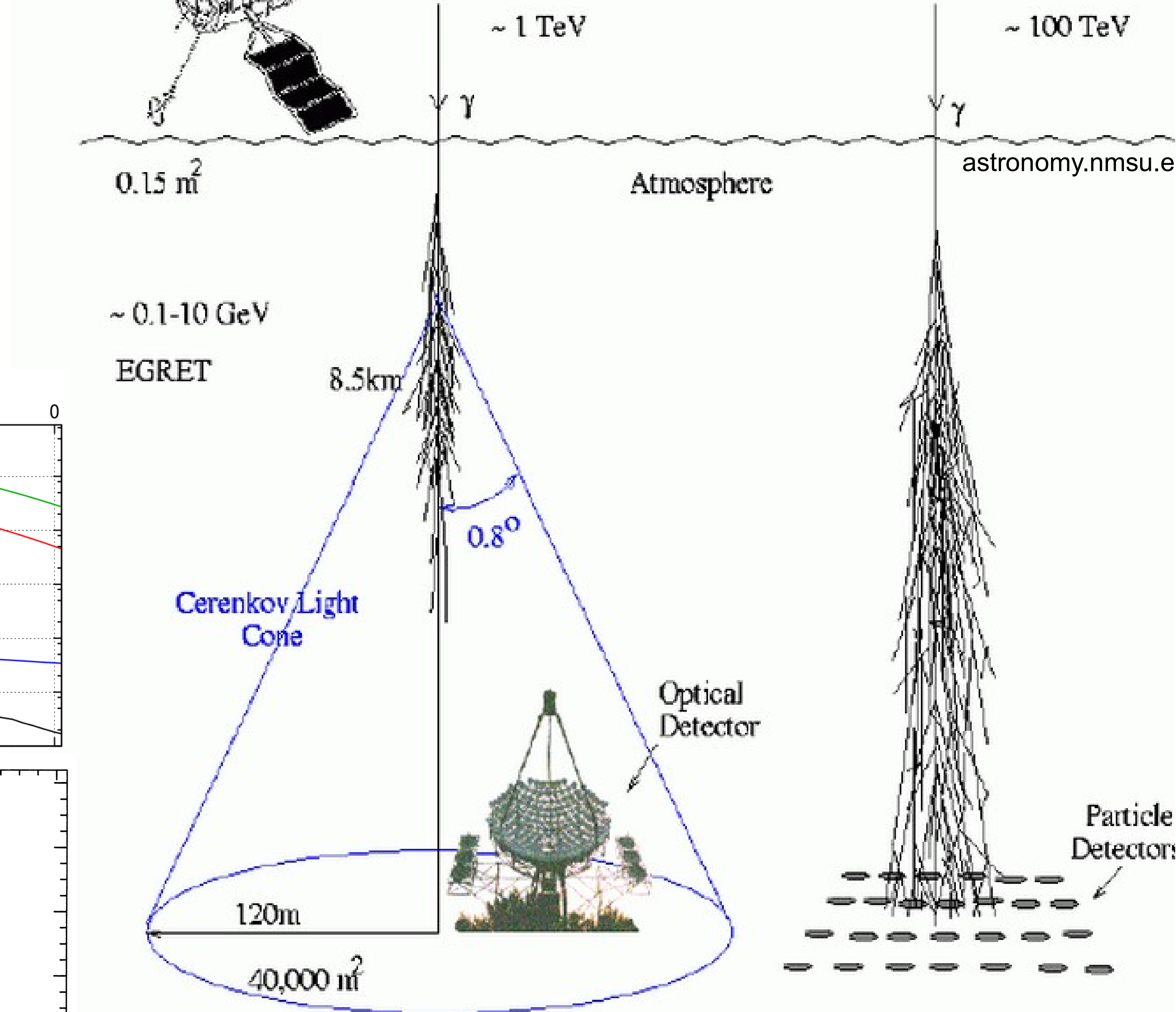

Cherenkov: "Integrating calorimeter"

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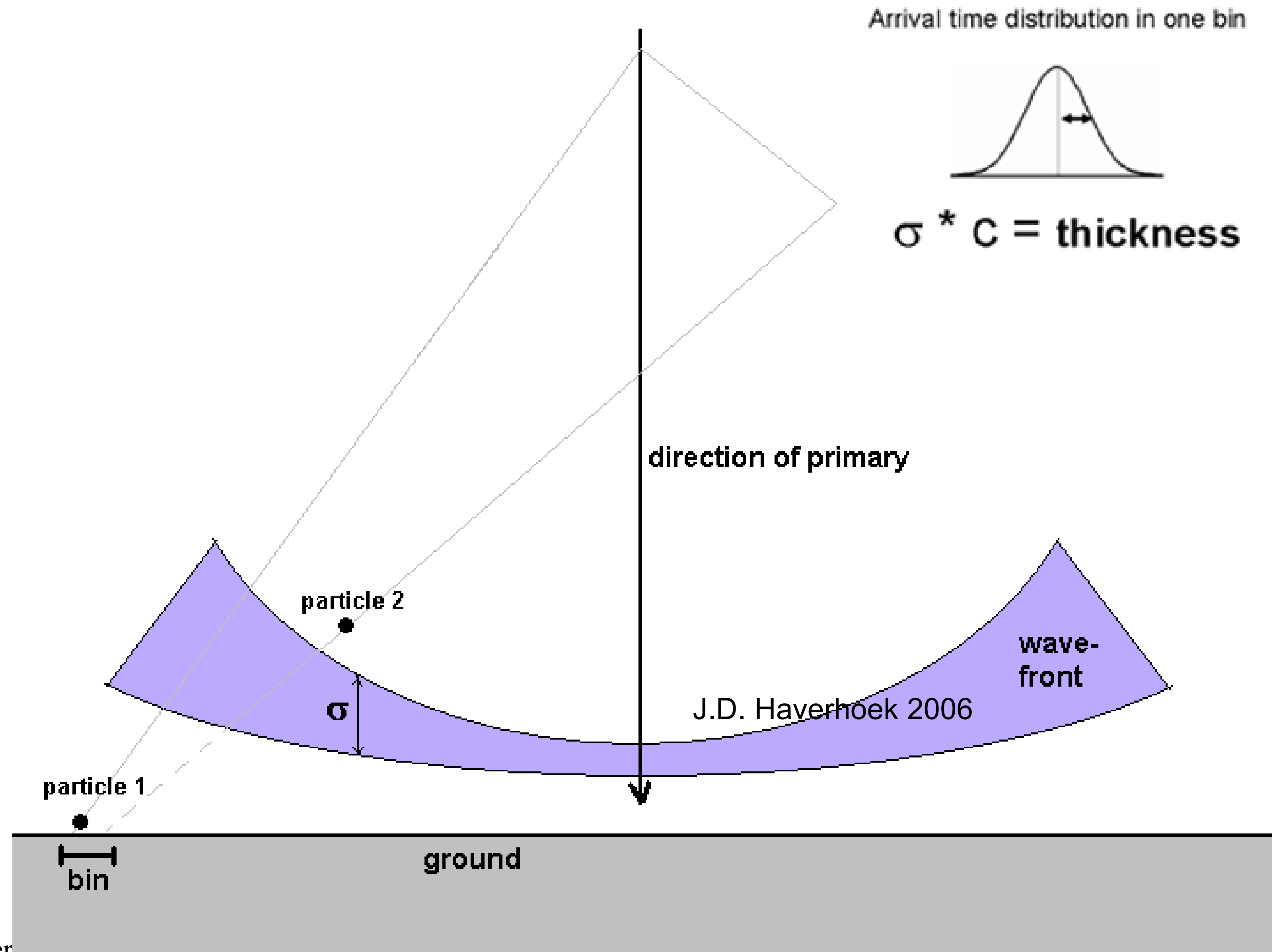
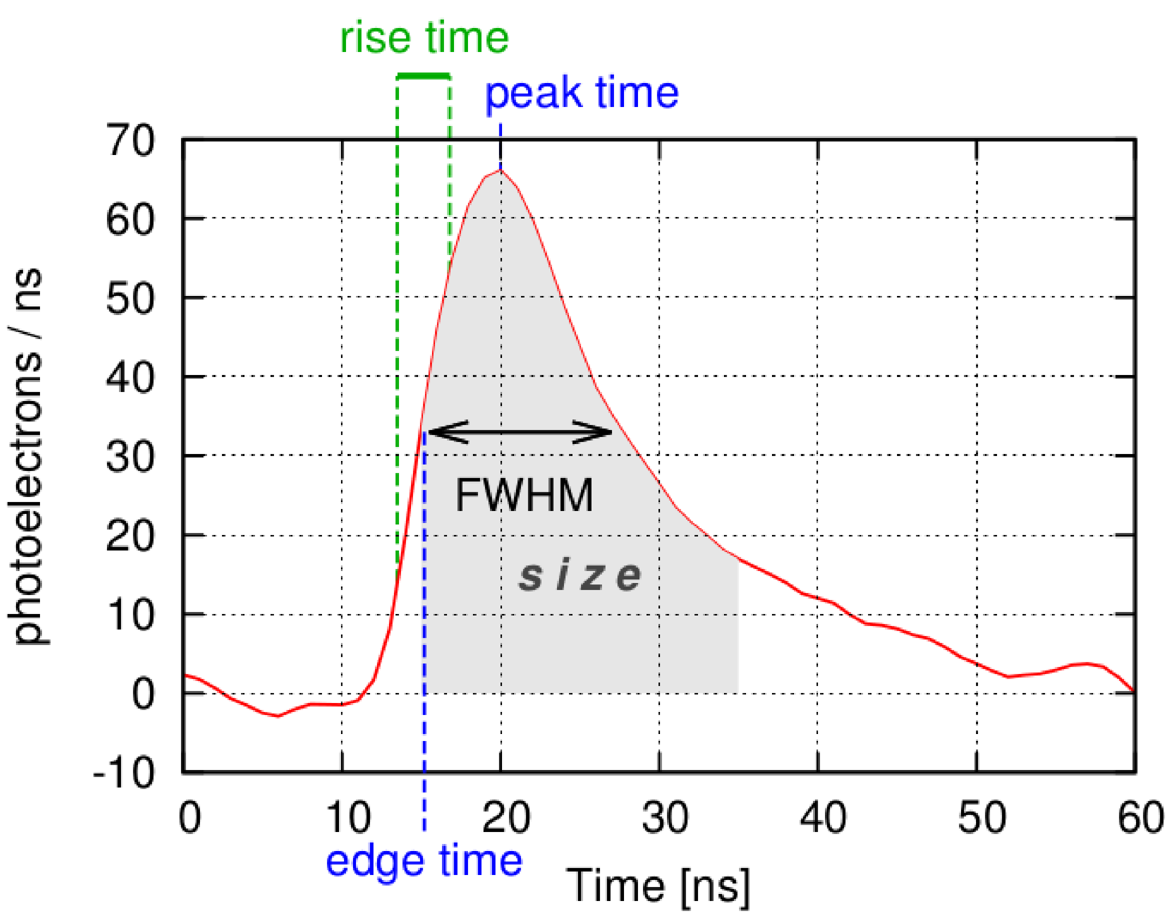
Timing of air showers



Timing of air showers

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



500 TeV
200 m

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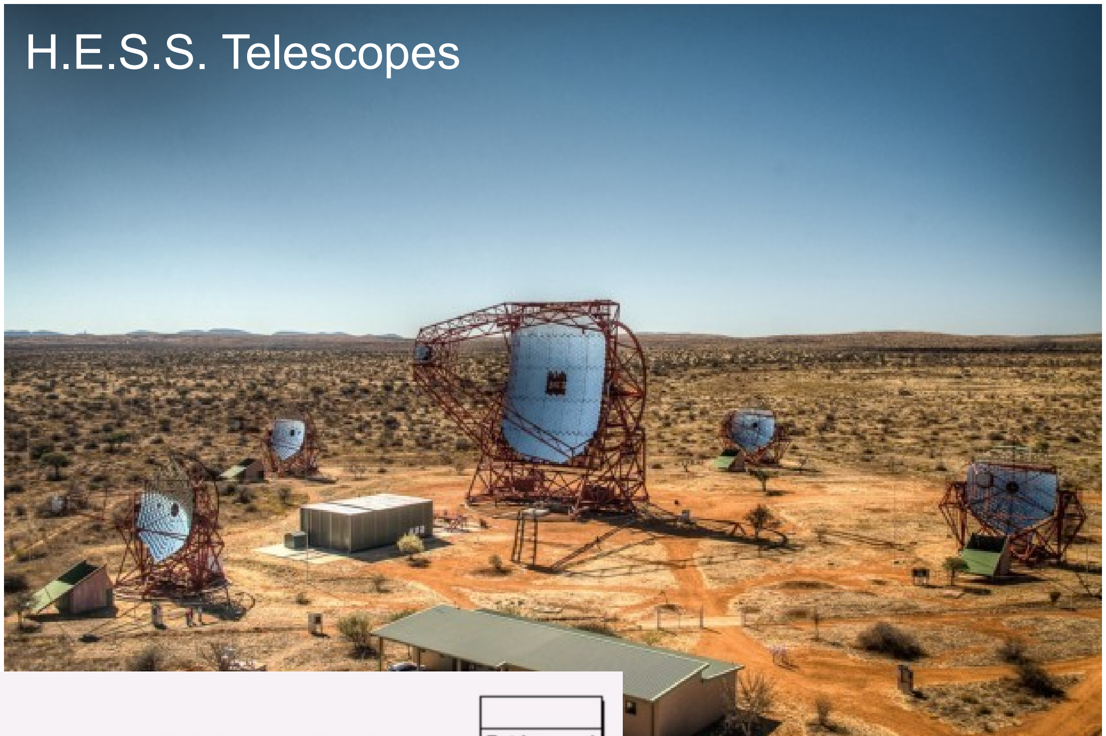
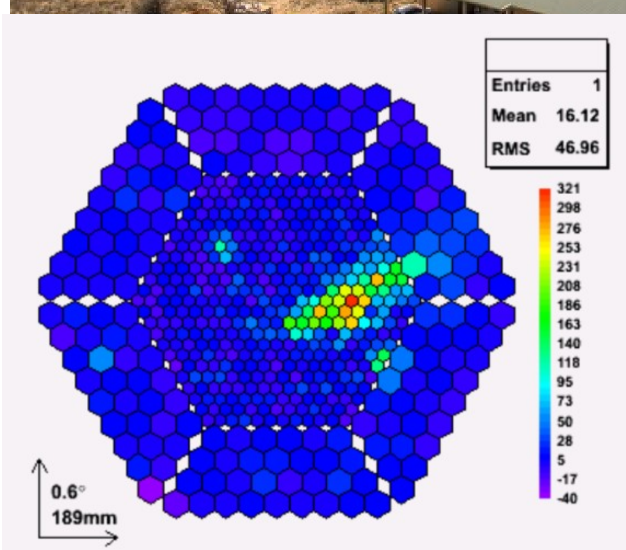
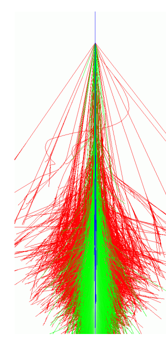
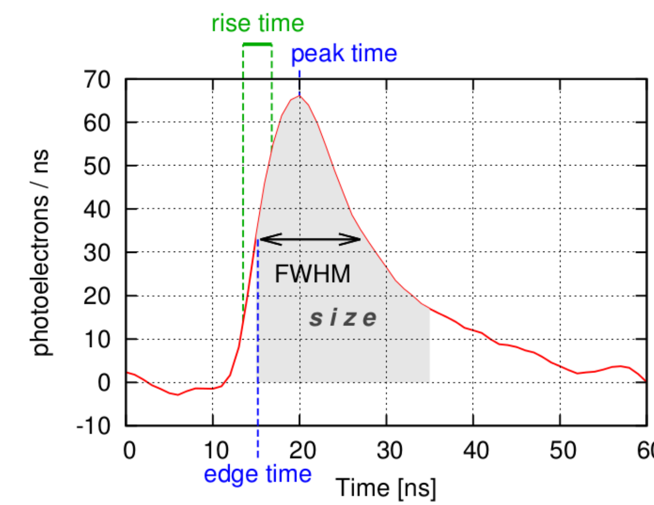
Air Cherenkov imaging and timing

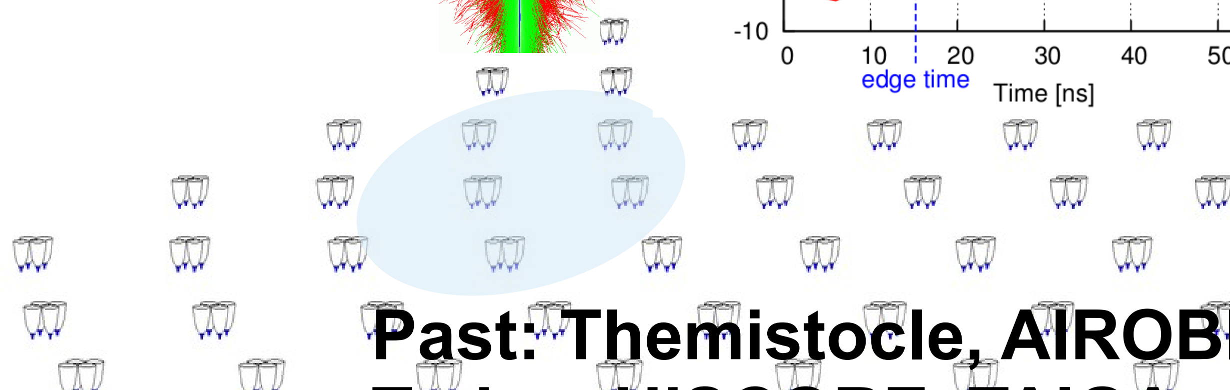




MAGIC camera image







Past: Themistocle, AIROBICC
Today: HiSCORE, TAIGA

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

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Upcoming timing arrays: HiSCORE and TAIGA

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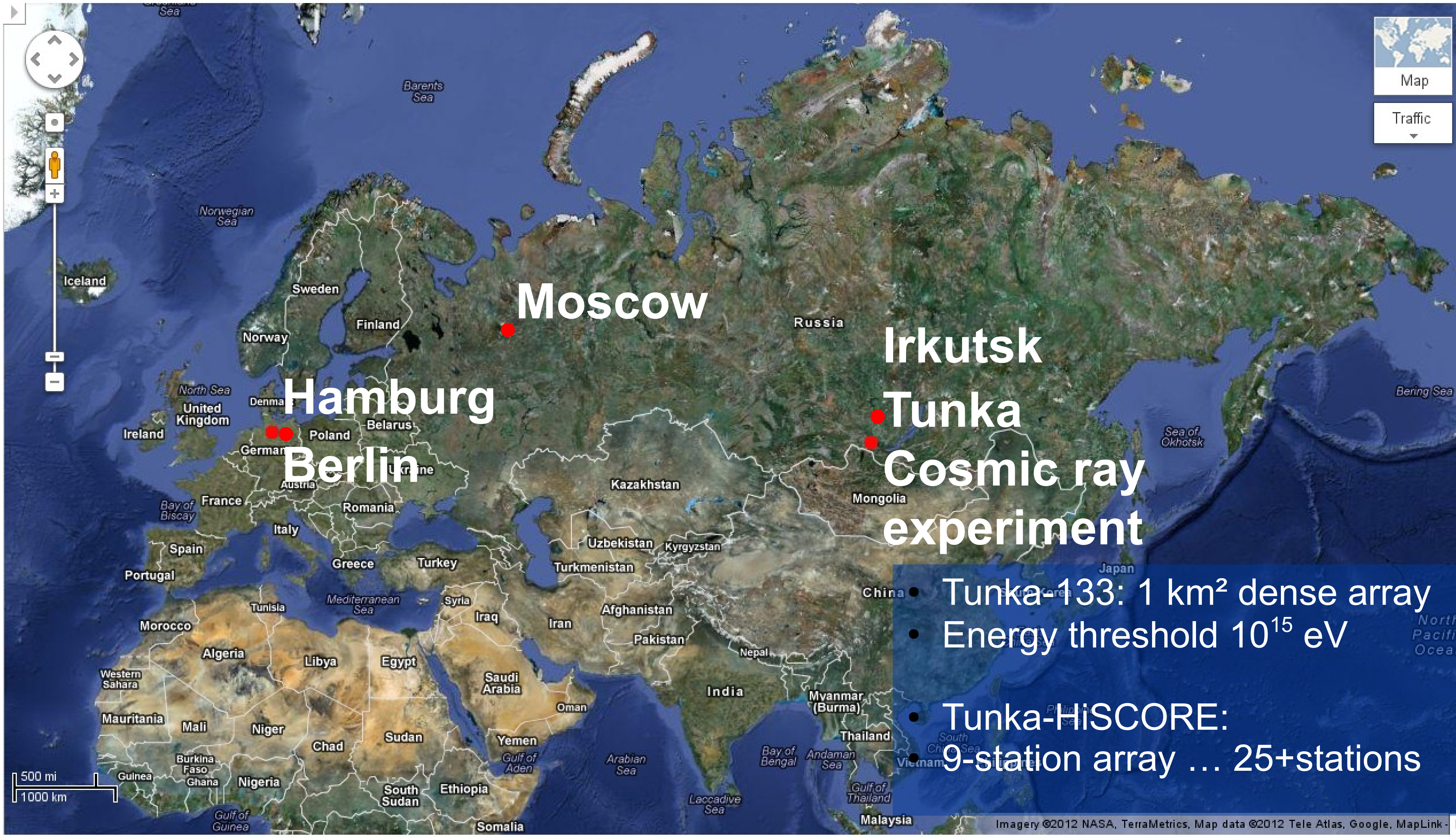
Tunka-HiSCORE



- Tunka-133: 1 km² dense array
- Energy threshold 10^{15} eV

- Tunka-HiSCORE:
- 9-station array … 25+stations

Tunka-HiSCORE Status

Prototype-array:

- 9 stations, 300m X 300m
- 150m inter-station distance
- 2 parallel DAQ systems
- Energy threshold: <30 TeV

Future:

- Projected E_{thr}: 10 TeV graded array and clipping

Station:

- 0.5 m² light collection
- 4 channels (PMT + Cone)

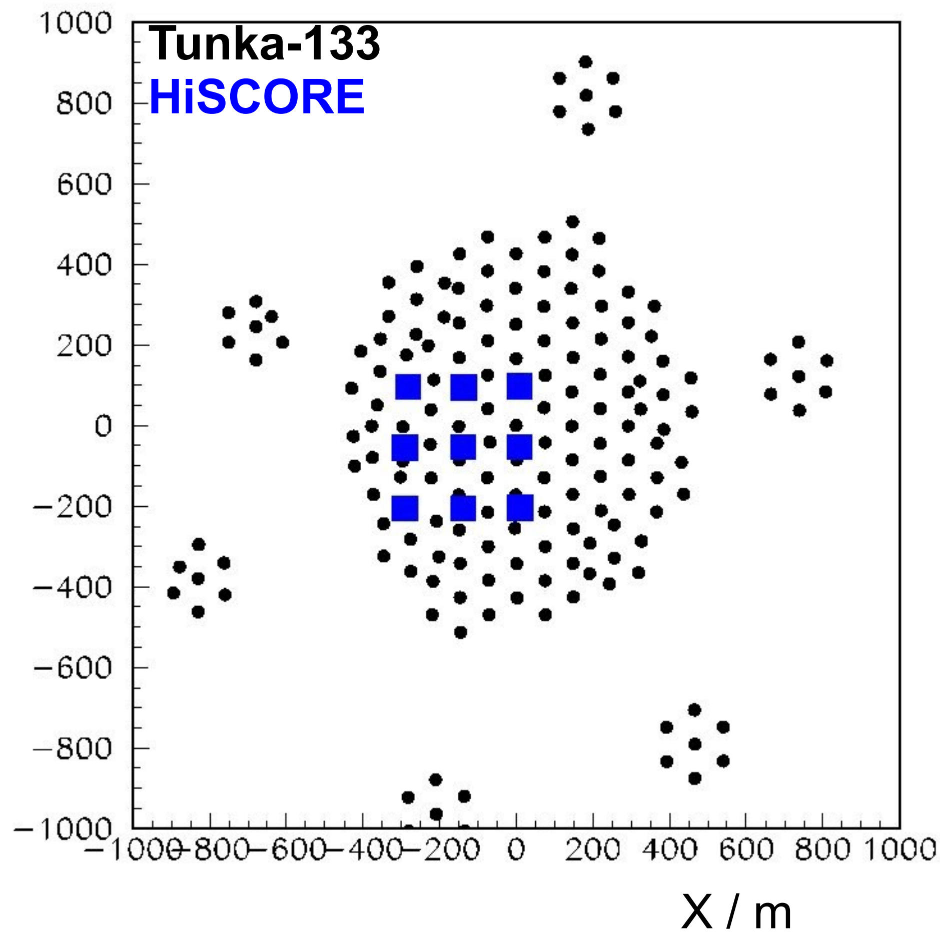
Tunka-HiSCORE Status

Prototype-array:

- 9 stations, 300m X 300m
- 150m inter-station distance
- 2 parallel DAQ systems
- Energy threshold: <30 TeV

Future:

- Projected E_{thr}: 10 TeV graded array and clipping



Also see:
Kozhin, V. “A DAQ System for Tunka-HiSCORE”, S8-234
Epimakhov, S. “Amplitude calibration for Tunka-HiSCORE”, S4-425

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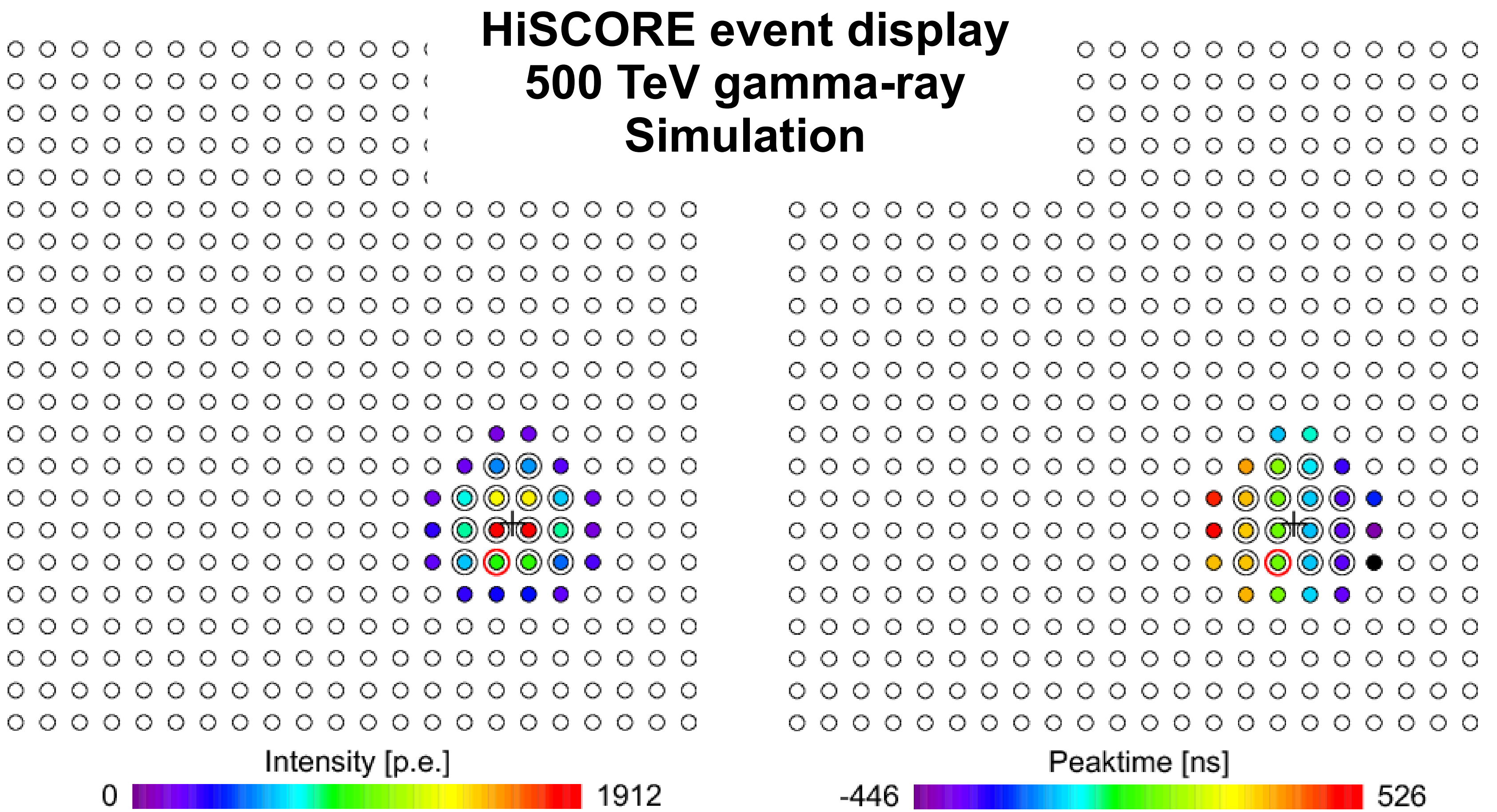
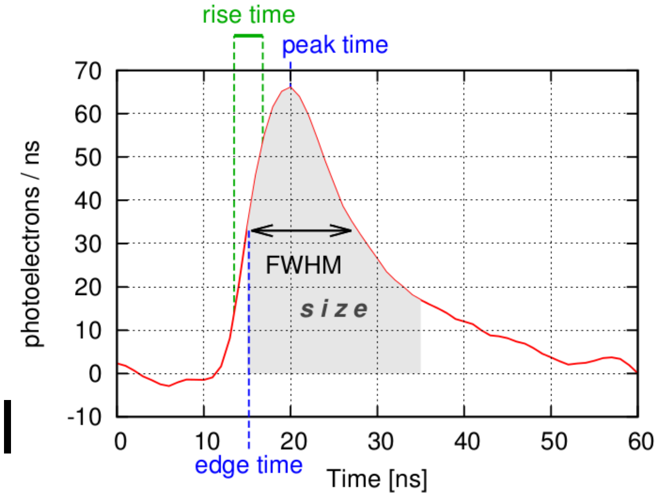
Reconstruction

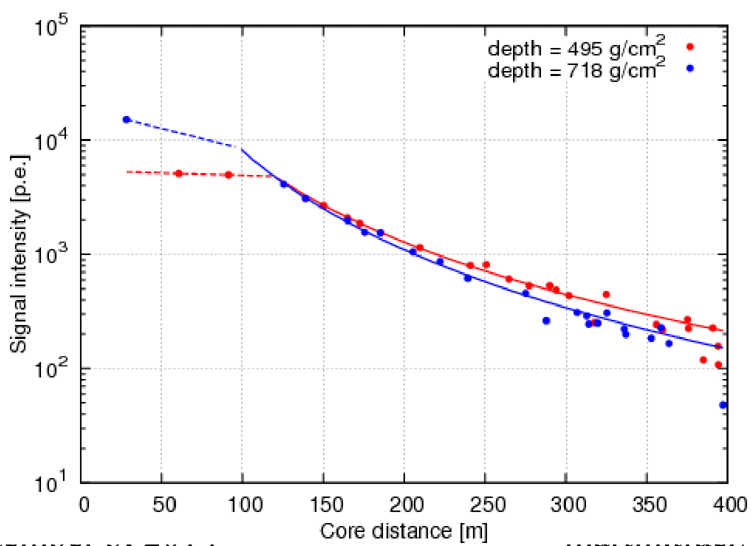
Tunka-133 [Berezhnev et al. 2012NIMPA.692...98B]
HiSCORE [Hampf et al. 2013NIMPA.712..137H]

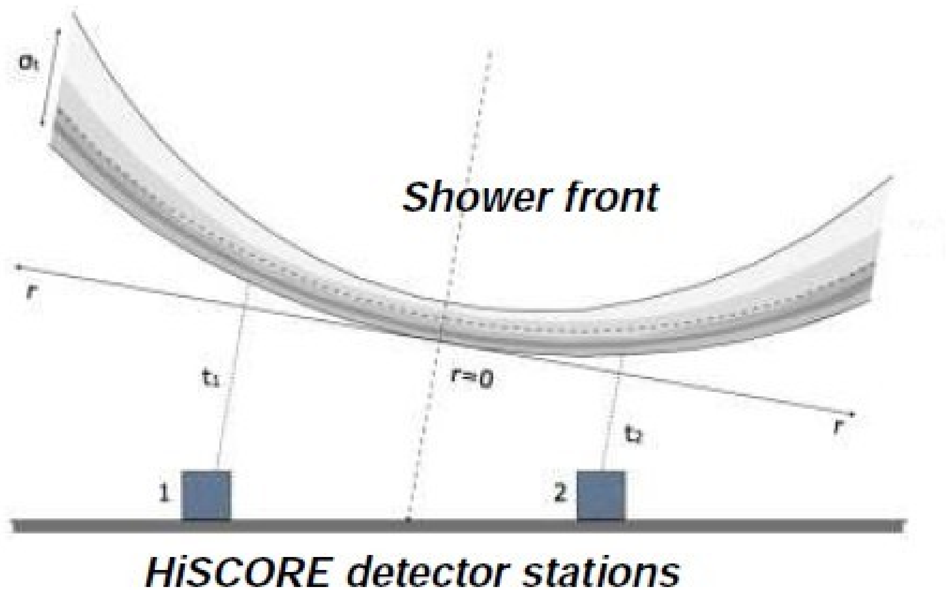


Reconstruction

- Shower core position 1 (cog)
- Preliminary direction (time plane fit)
- Improved core position:
  light distribution function (LDF) fitting
- Improved direction: arrival time model
- Fit of signal time widths

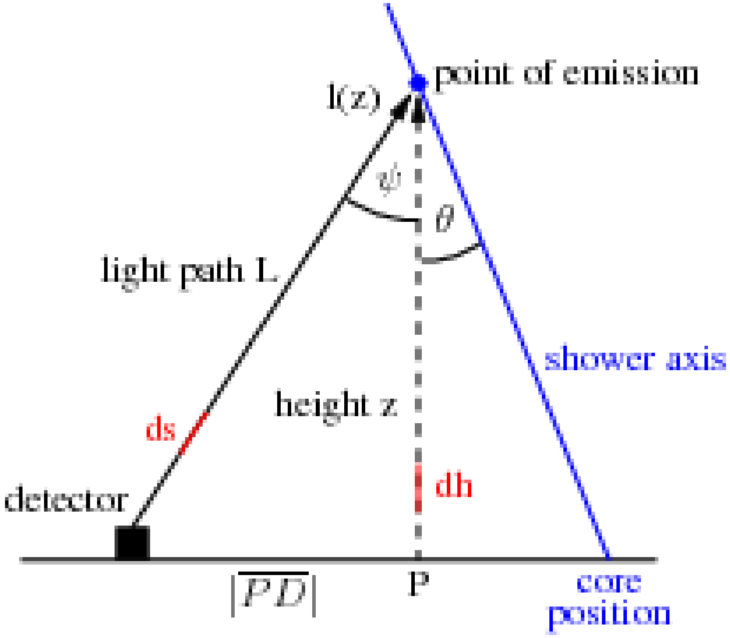






Arrival time model

2013NIMPA.712..137H



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

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

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

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Arrival time model

r: Distance from shower core to detector

Slope of atmospheric refractive index

Shower height in km

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

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

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

Zenith angle

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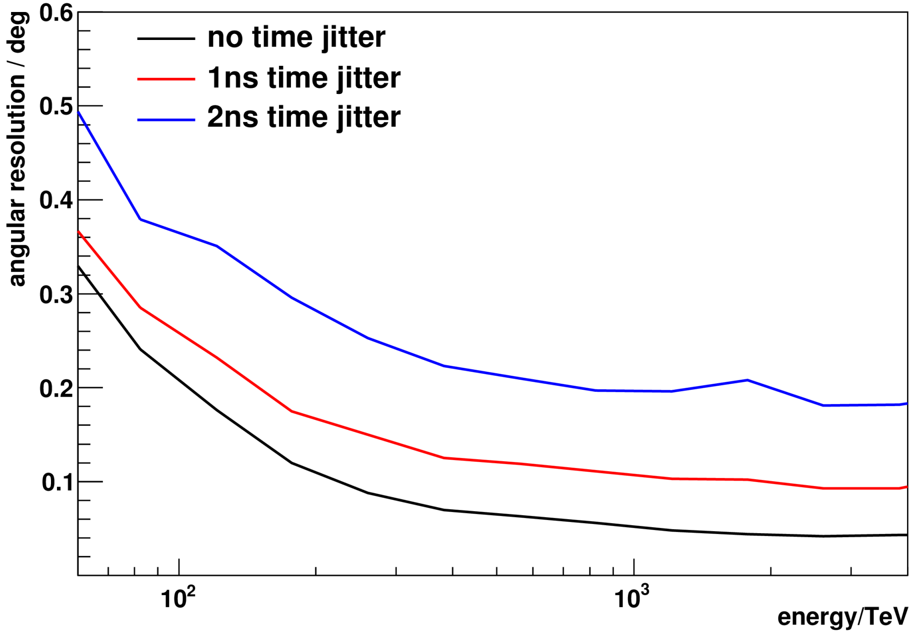
Angular resolution



Crucial: relative time-synchronization <1ns

Two time-calibration systems:

DRS4 sampling of 100 MHz frequency

WhiteRabbit system

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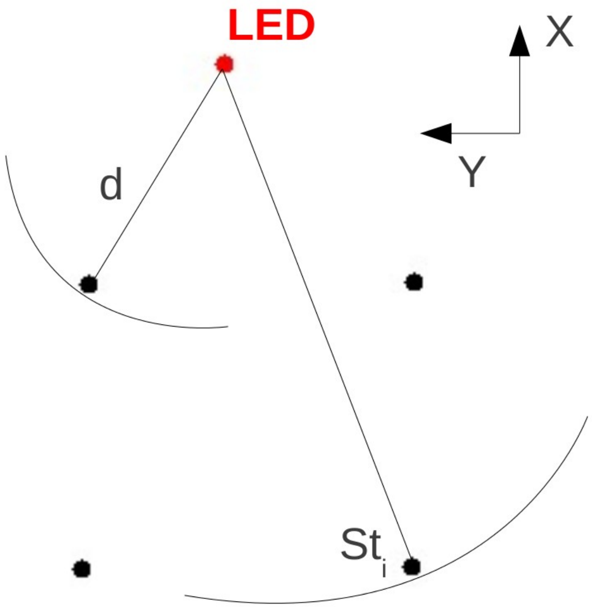
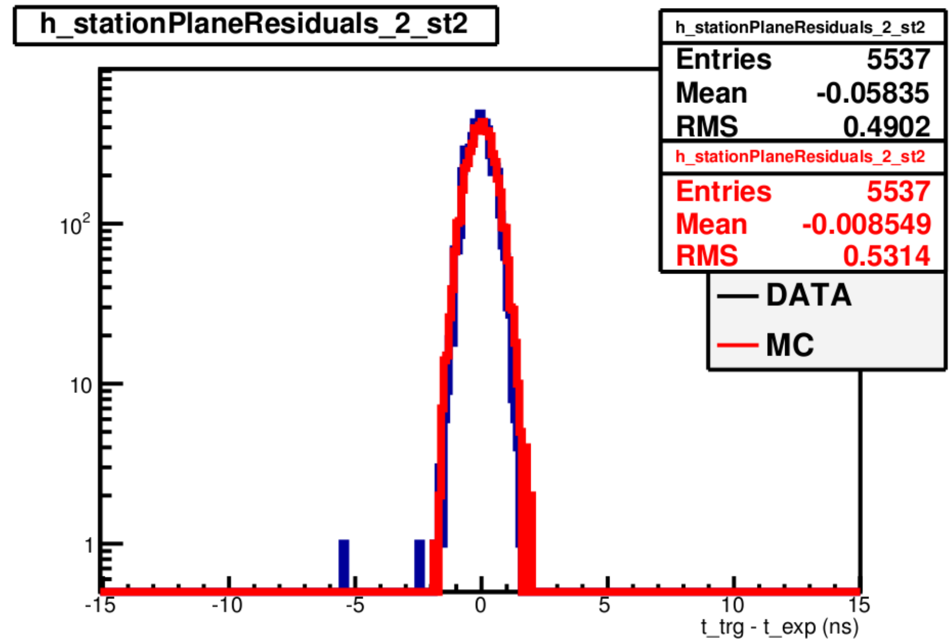
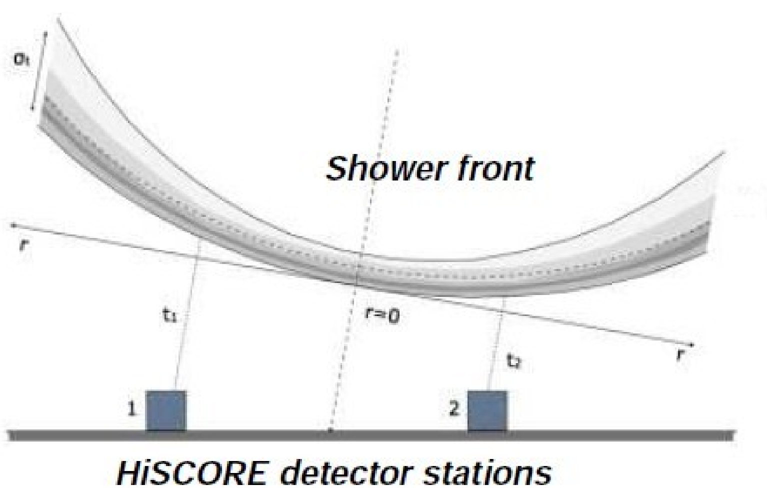
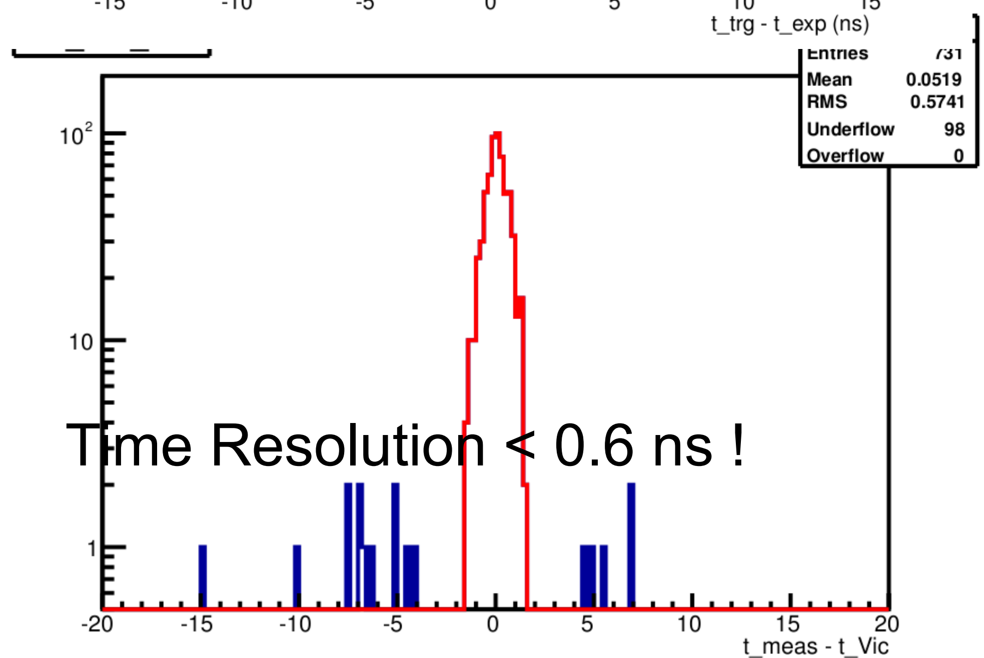
Time calibration







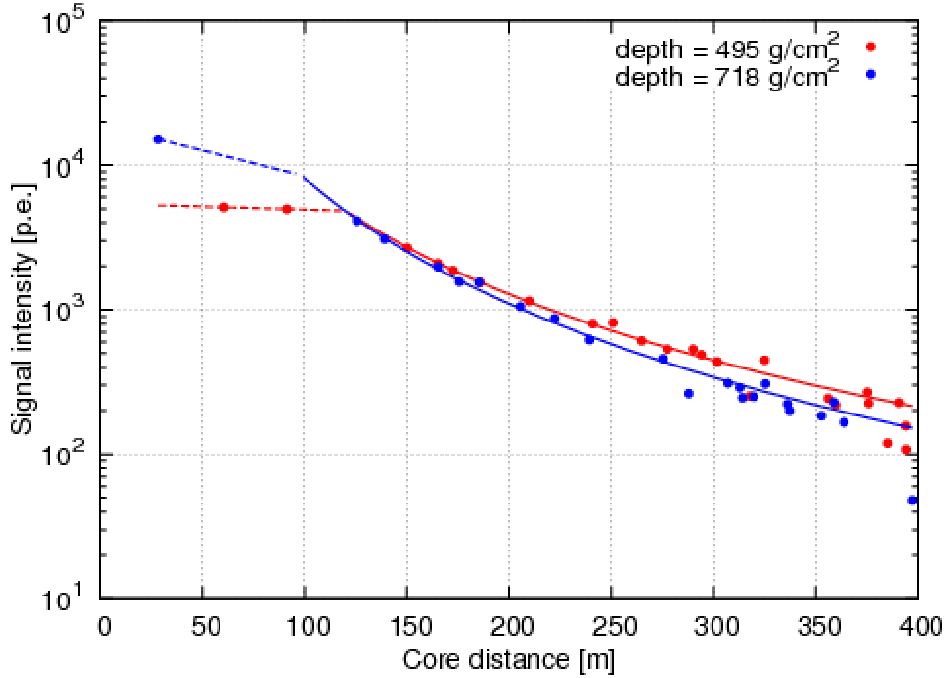


Time Resolution < 0.6 ns !

Energy determination

Energy → light density

Q(x) = LDF at x m



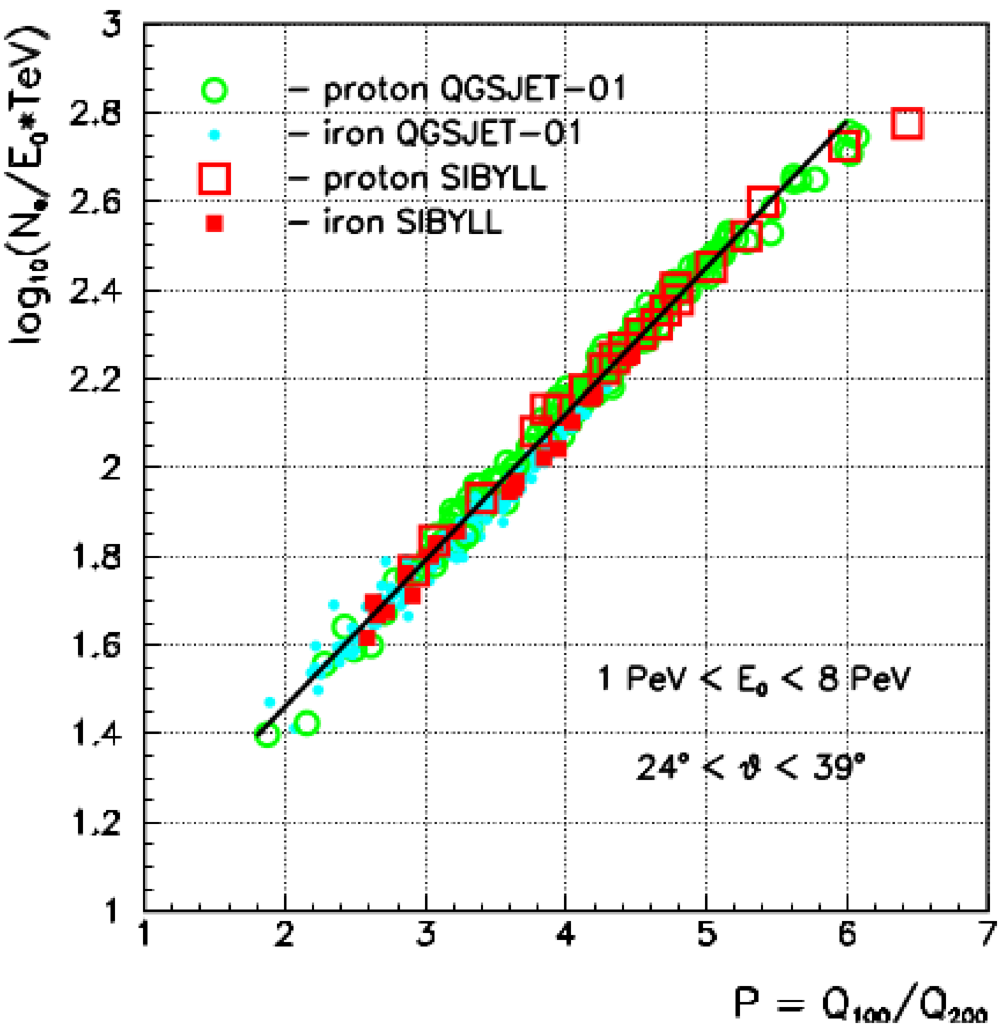
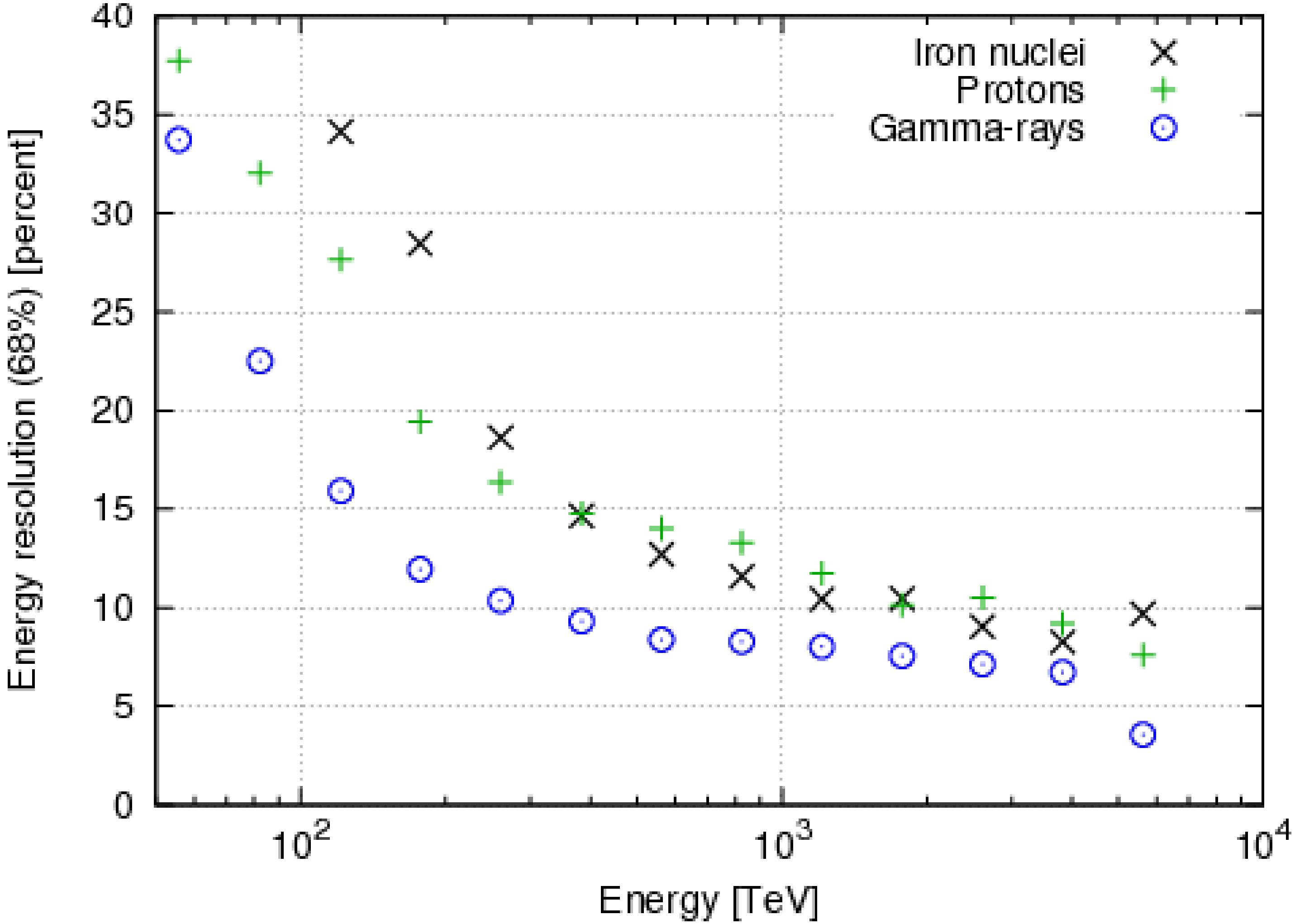


Figure 2: N_e/E_0 vs P

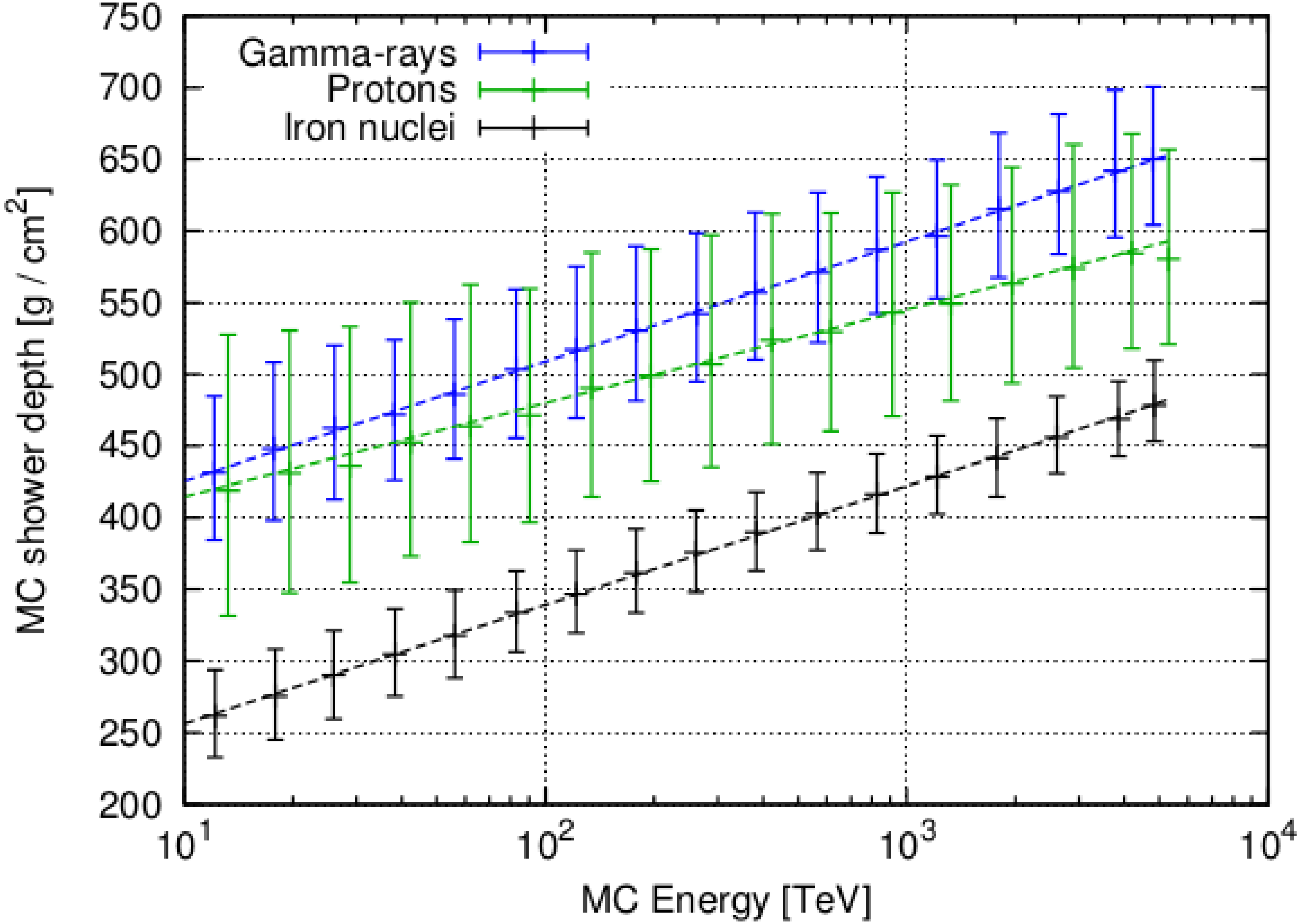
2012NIMPA.692...98B

Energy determination

HiSCORE simulation



Particle separation Xmax vs. E



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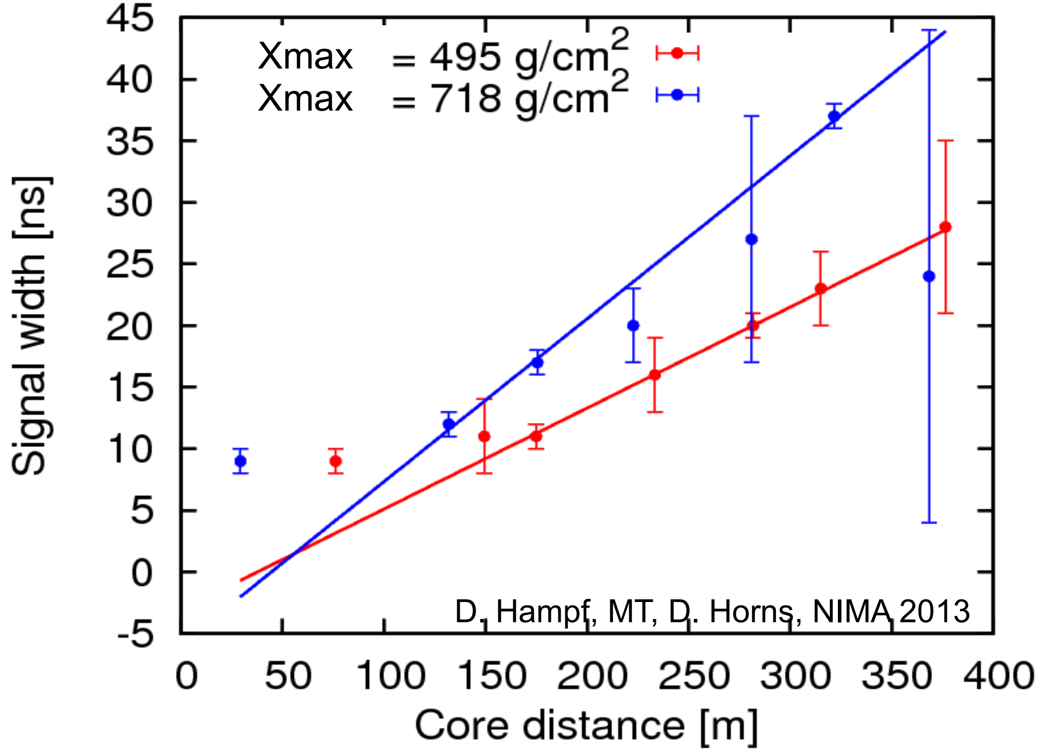
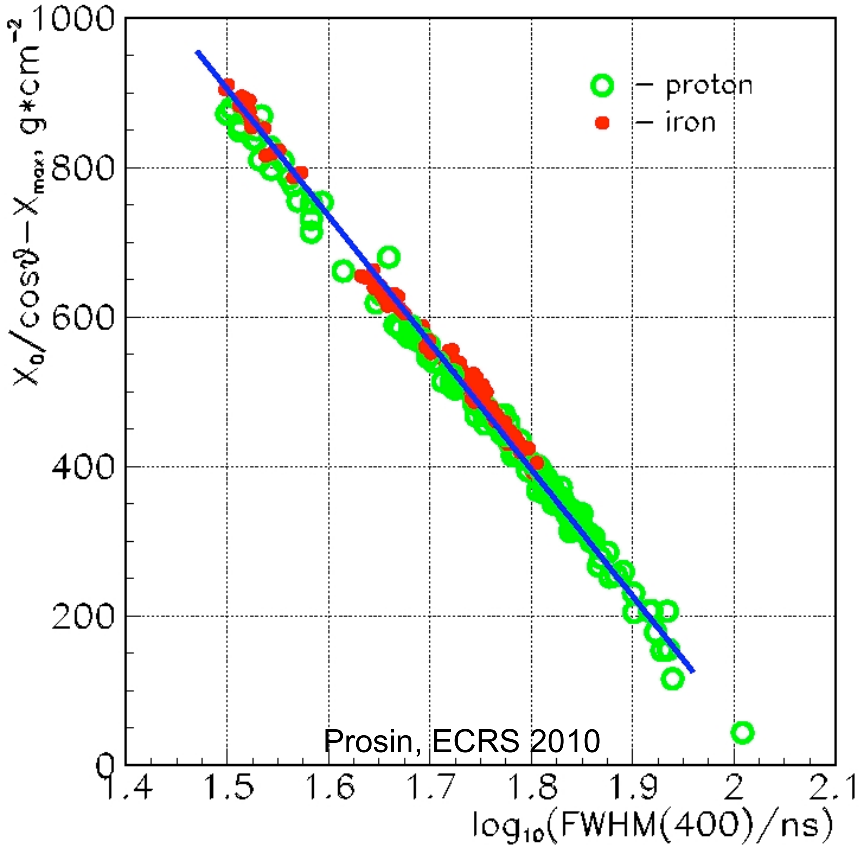
Shower maximum

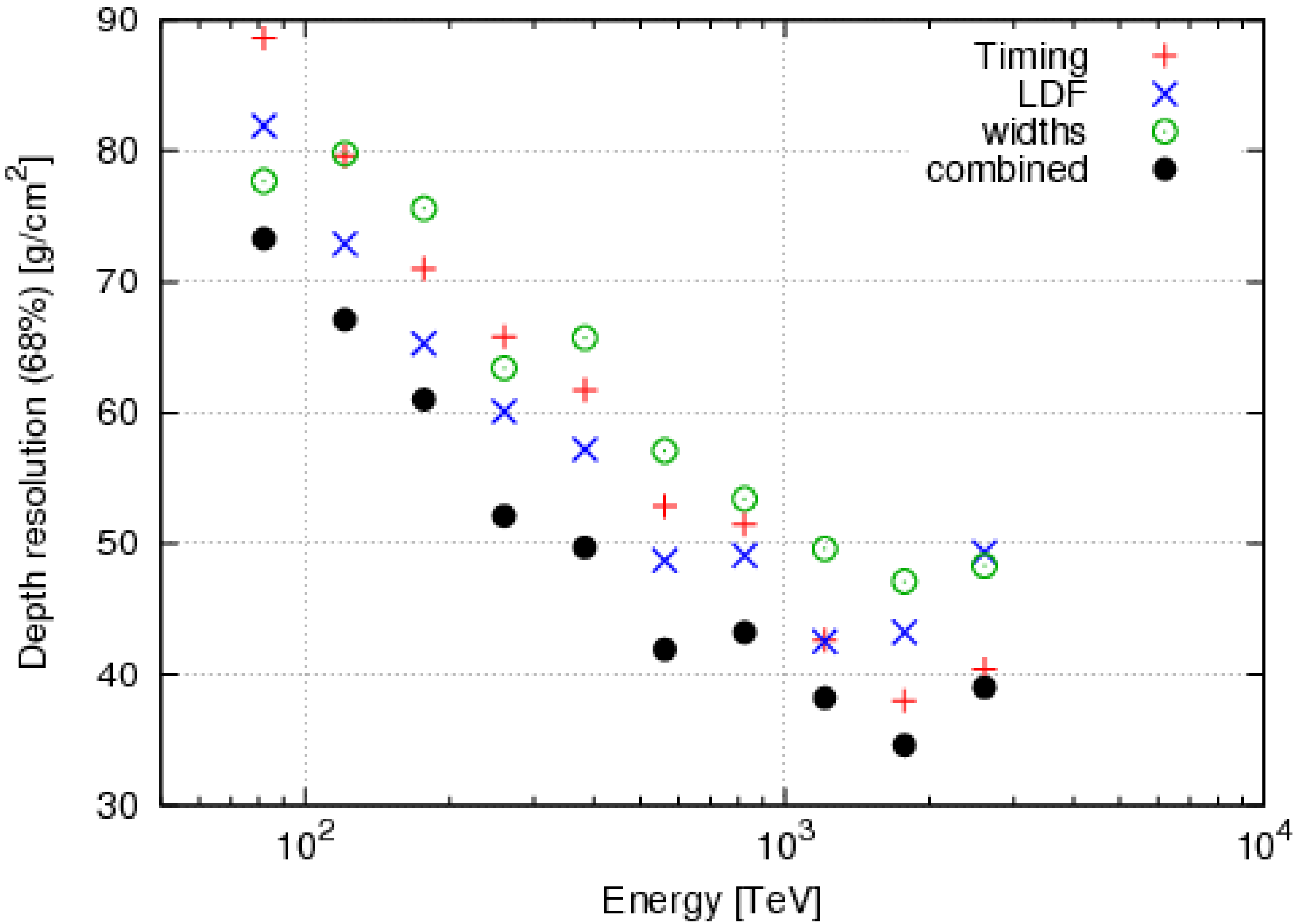
- **Time model method:** X_{max} free parameter in arrival time model
- **LDF method:** X_{max} from LDF slope, Q50/Q220
- **Width method:** X_{max} from signal width



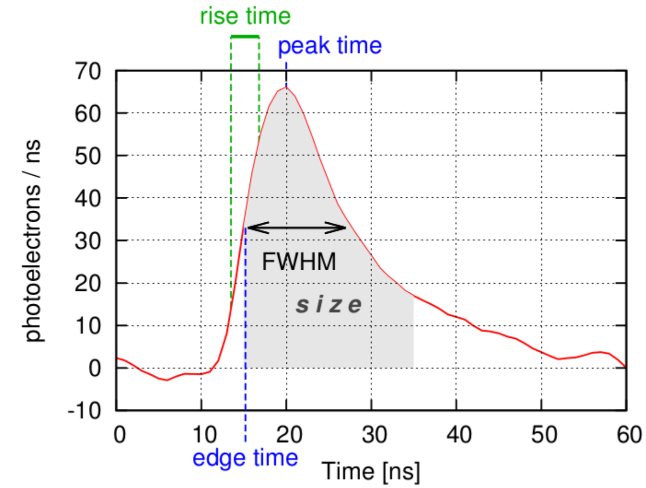


Shower maximum

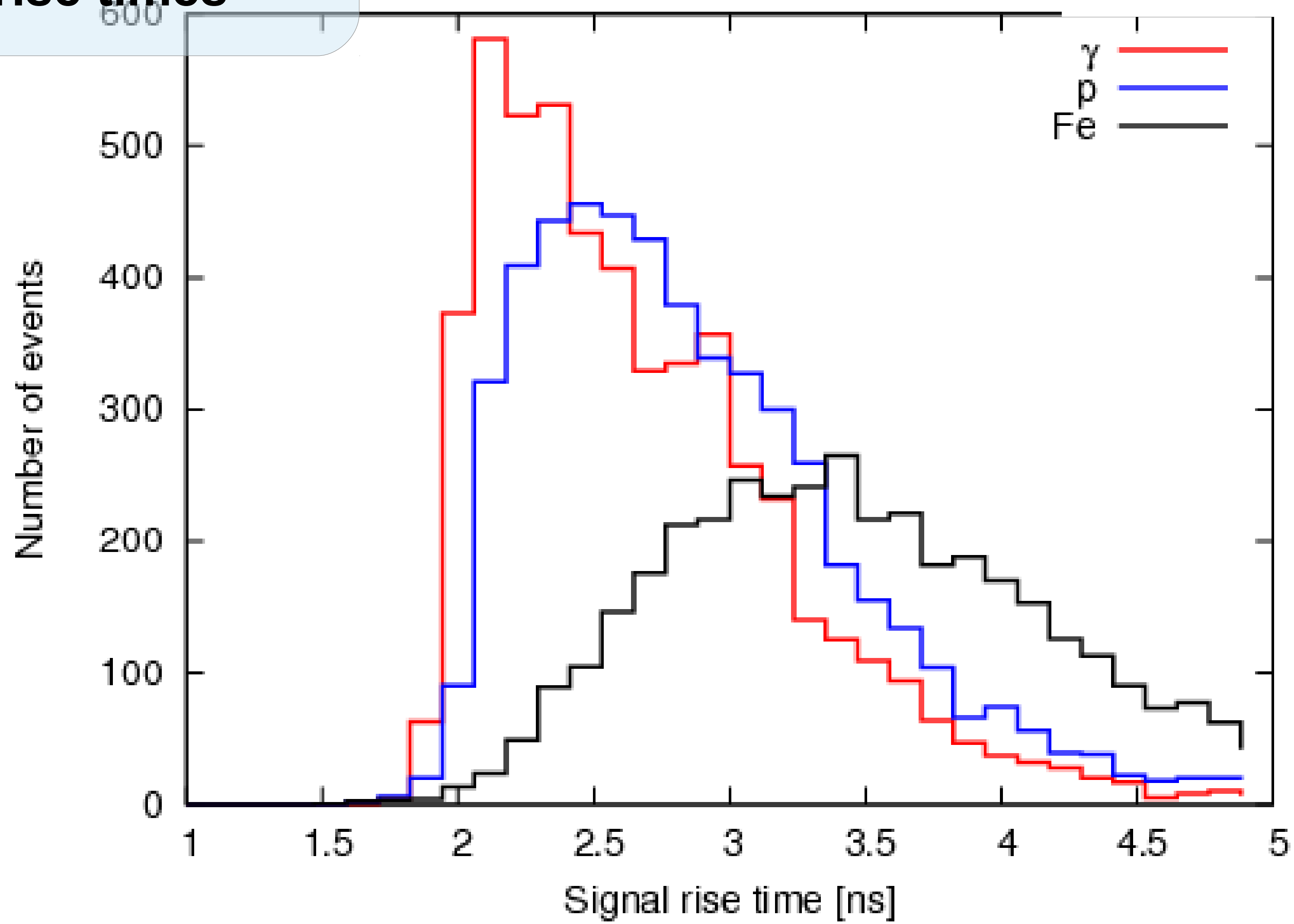
HiSCORE Simulation



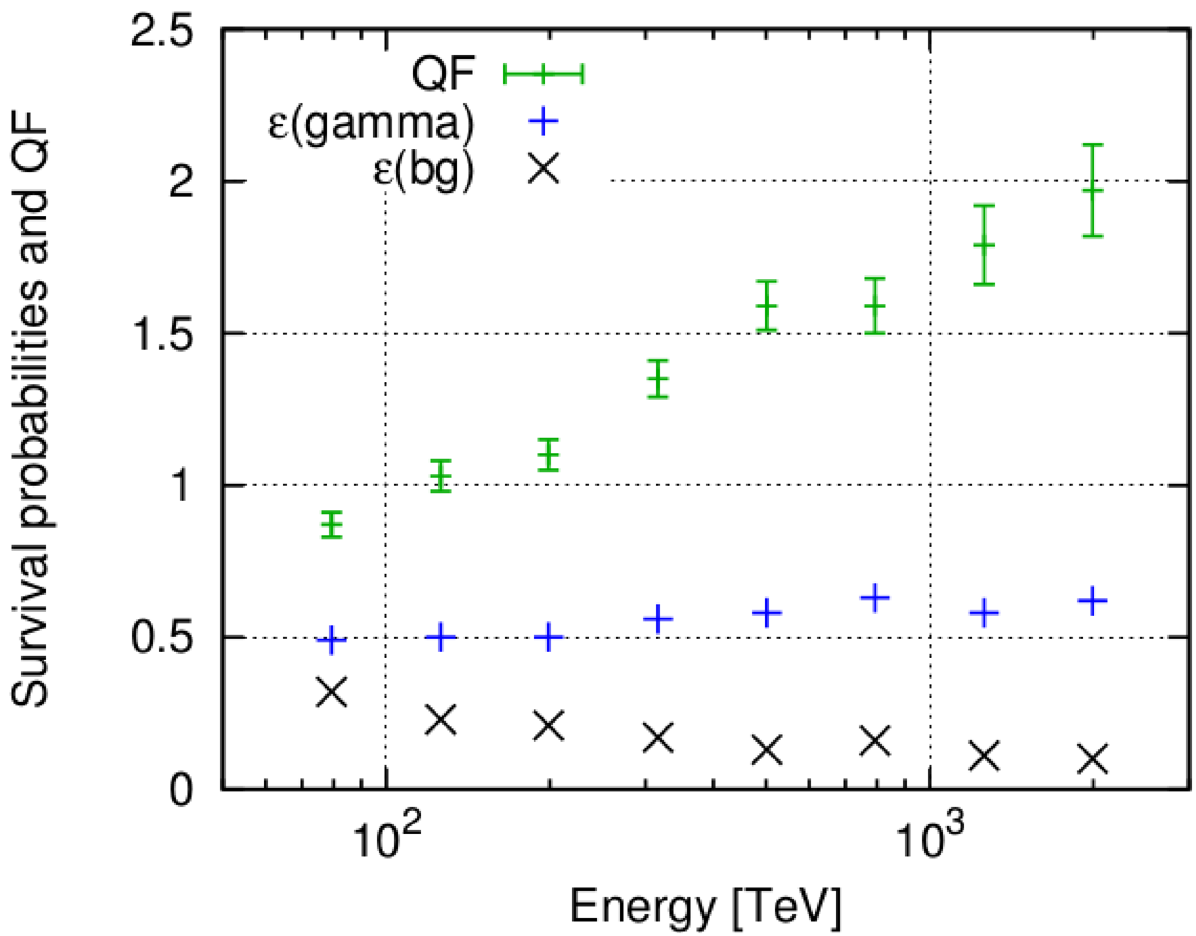
Particle separation timing



Systematic difference Cherenkov signal **rise times**



Particle separation Q-factor



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

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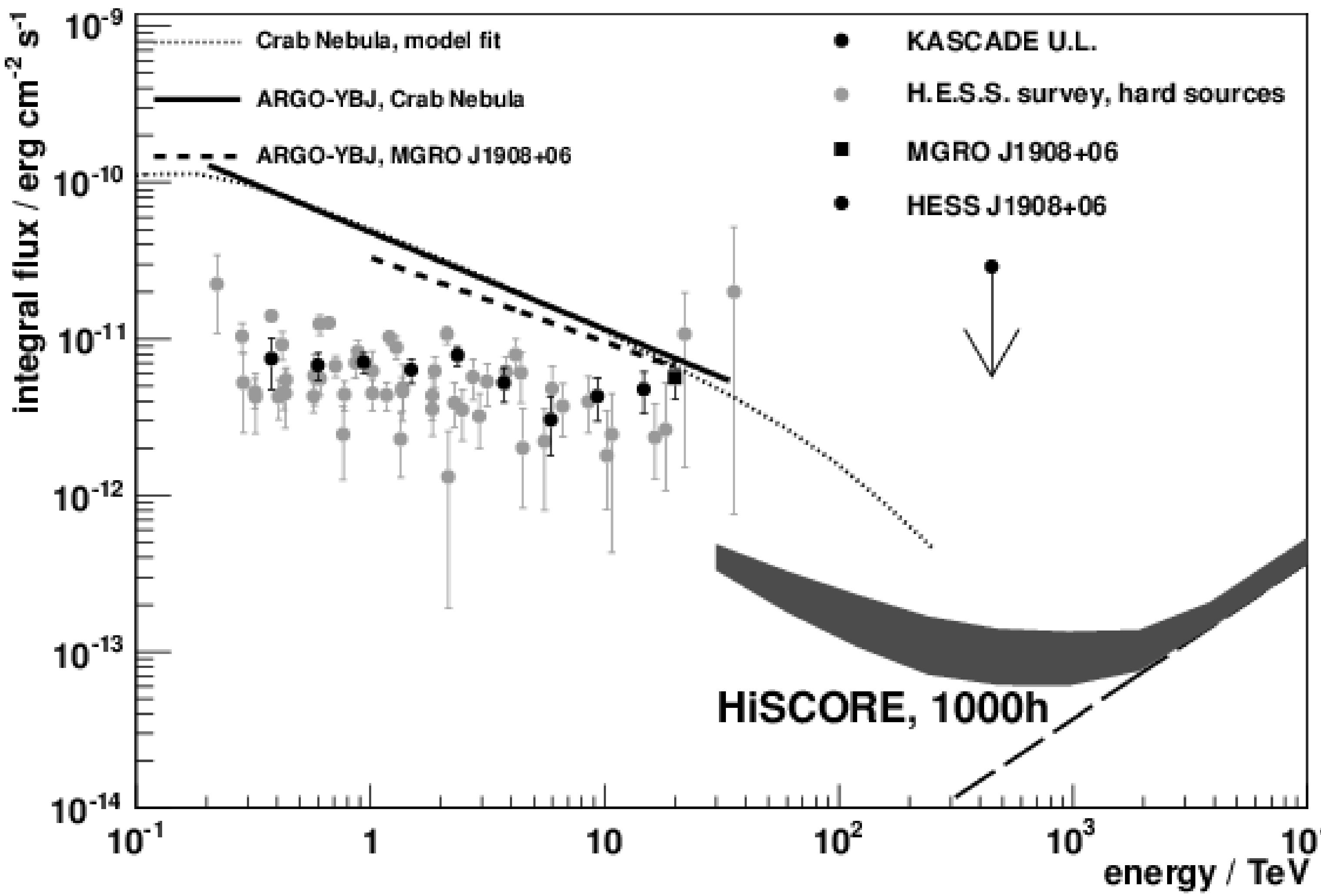
Sensitivity



Tunka-HiSCORE → TAIGA

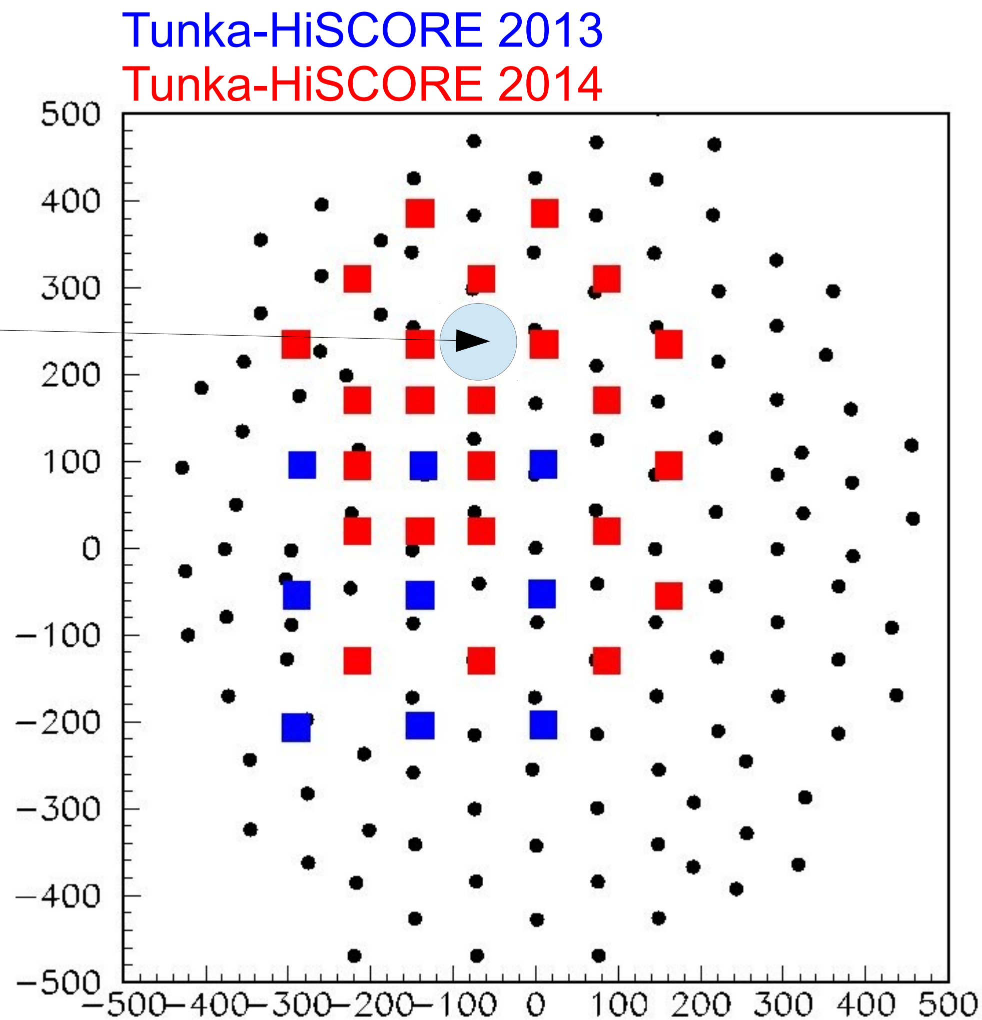
Tunka Advanced Instrument for Gamma ray and cosmic ray physics

10/2014: extension

- Additional 25 stations
- First telescope
- Tilting mode

2015+:

- 10 telescopes
- Hybrid timing+imaging
- Muon detectors



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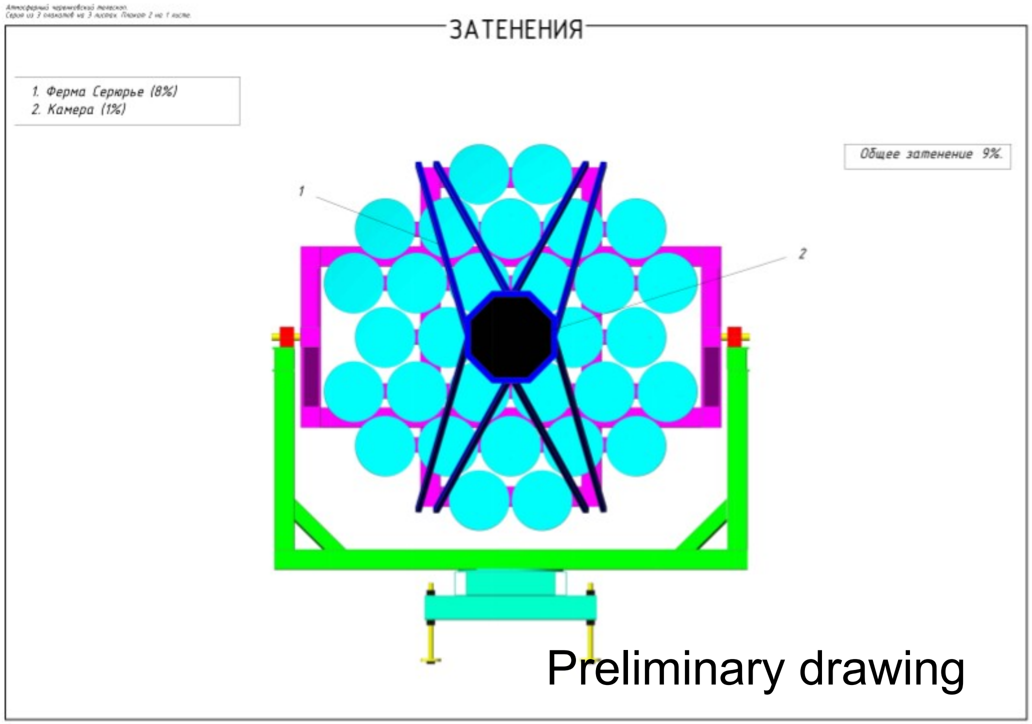
TAIGA Telescopes



- Dish: Davies-cotton tesselated, 34 mirrors (60cm)
- 4.3 m dish diameter
- 4.75 m focal length
- F/D ~ 1.2
- 397 PMT camera foV 8° (0.38° / pixel)
- Proven design components

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Non-imaging and imaging hybrid detection

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Telescope image scaling

Central reconstruction parameter: Shower core position D_K

$$w_{\mathrm{MC}} = w_{\mathrm{MC}}(size, \mathrm{D_K}, \vartheta)$$

$$mscw = \frac{1}{\mathrm{N_{Tel}}} \sum_{\mathrm{k=1}}^{\mathrm{N_{Tel}}} \frac{width}{w_{\mathrm{MC}}}$$

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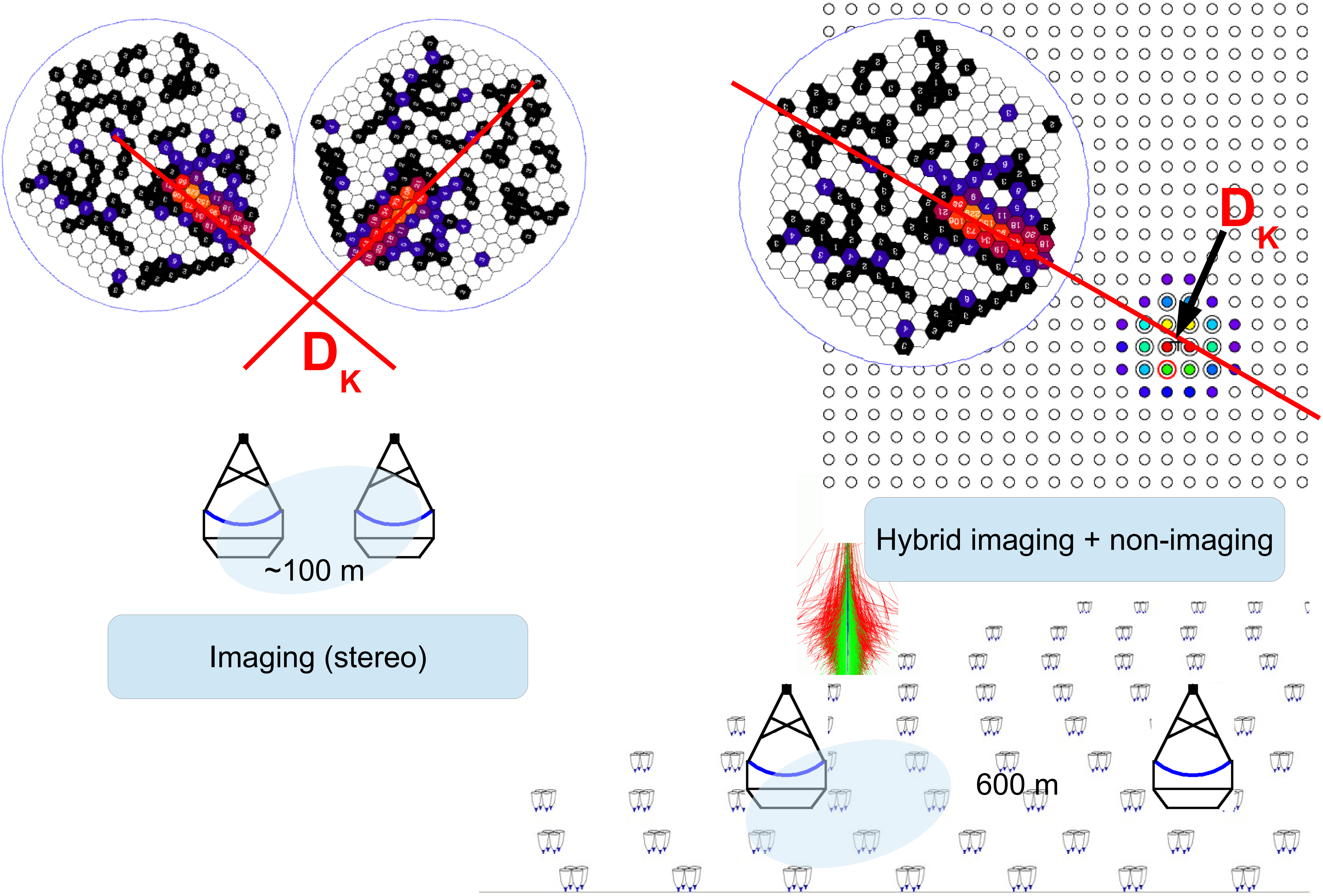
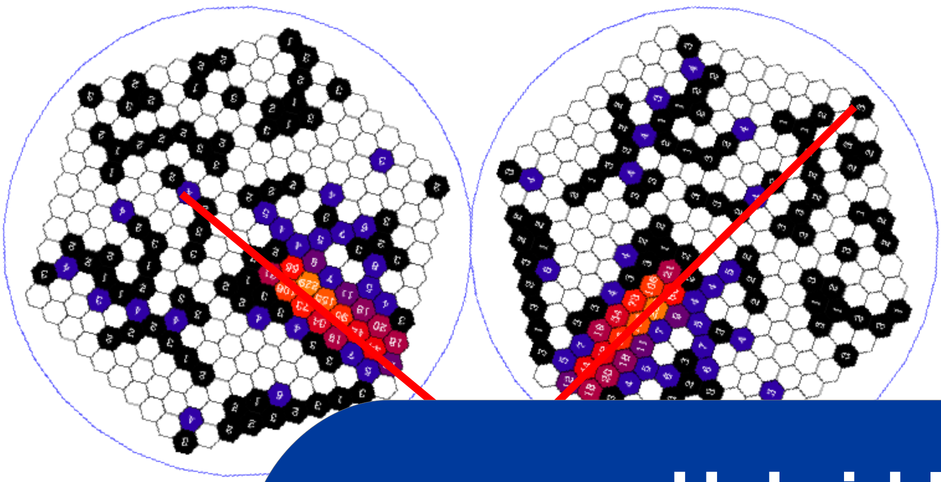
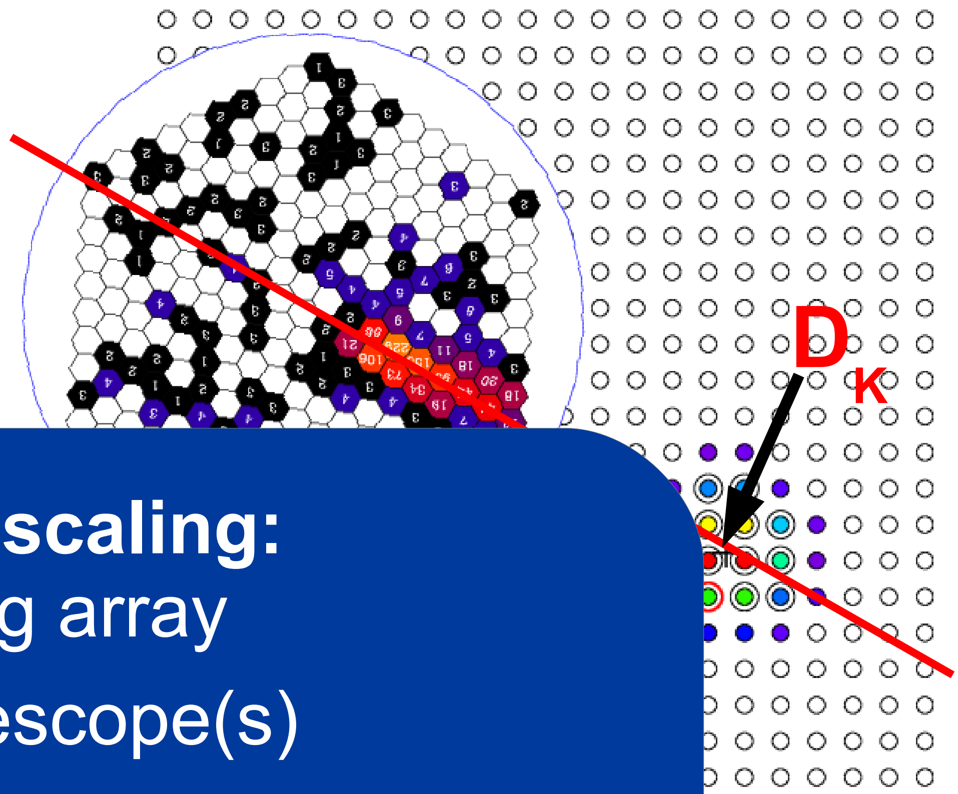

D_K
~100 m
Imaging (stereo)
D_K
Hybrid imaging + non-imaging
600 m





Hybrid Image scaling:

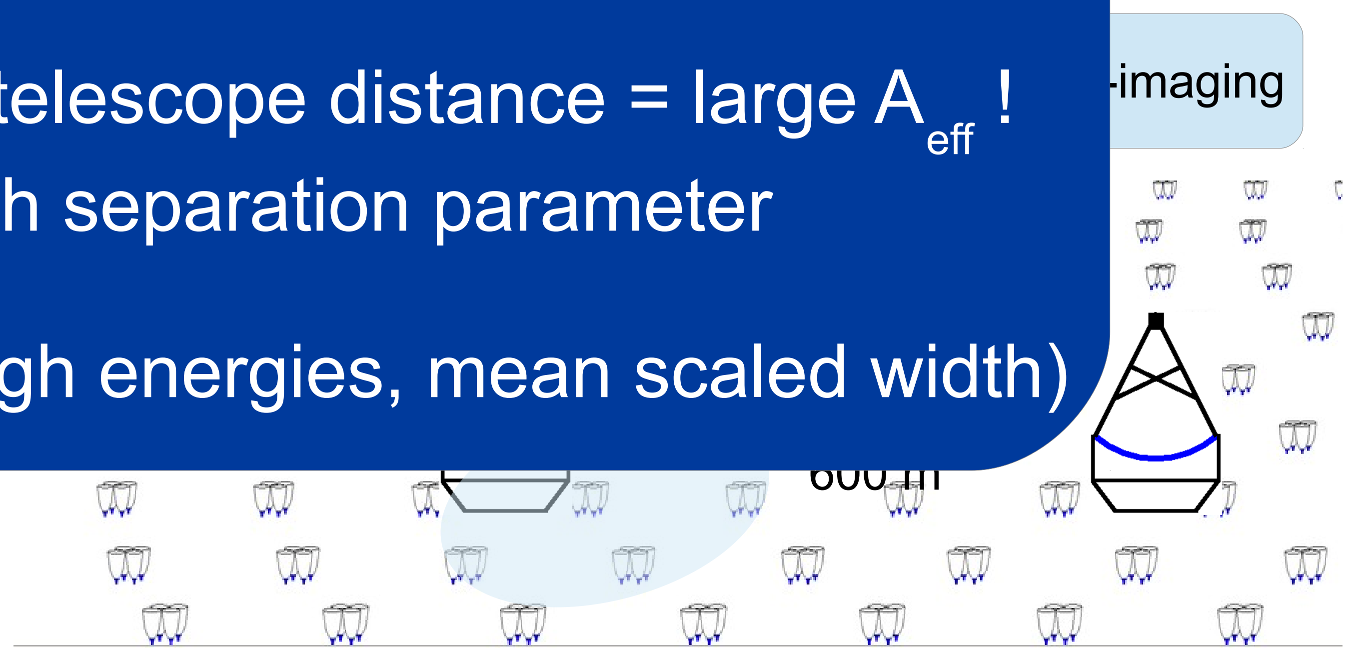
D_K from timing array

Image from telescope(s)

→ large inter-telescope distance = large A_{eff} !

→ scaled width separation parameter

(+ stereo at high energies, mean scaled width)



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HiSCORE + IACTs

Preliminary results hybrid width scaling:

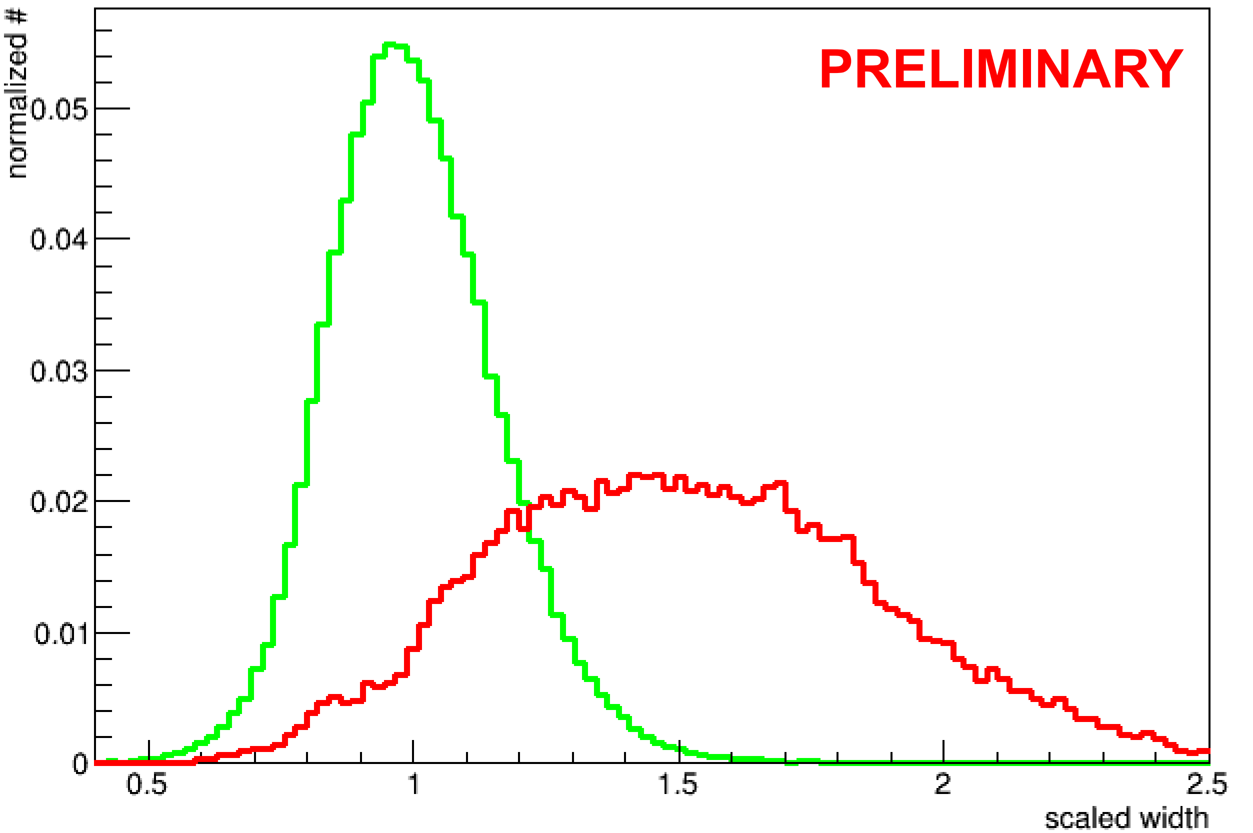
- Improves gamma-hadron separation
- Increases total area as compared to stereoscopic array

Also see:
Kunnas, M.
"Simulation of TAIGA"

Apply scaled width cut:

Q-factor ~2.2

(Simulated granularity: 0.5°)



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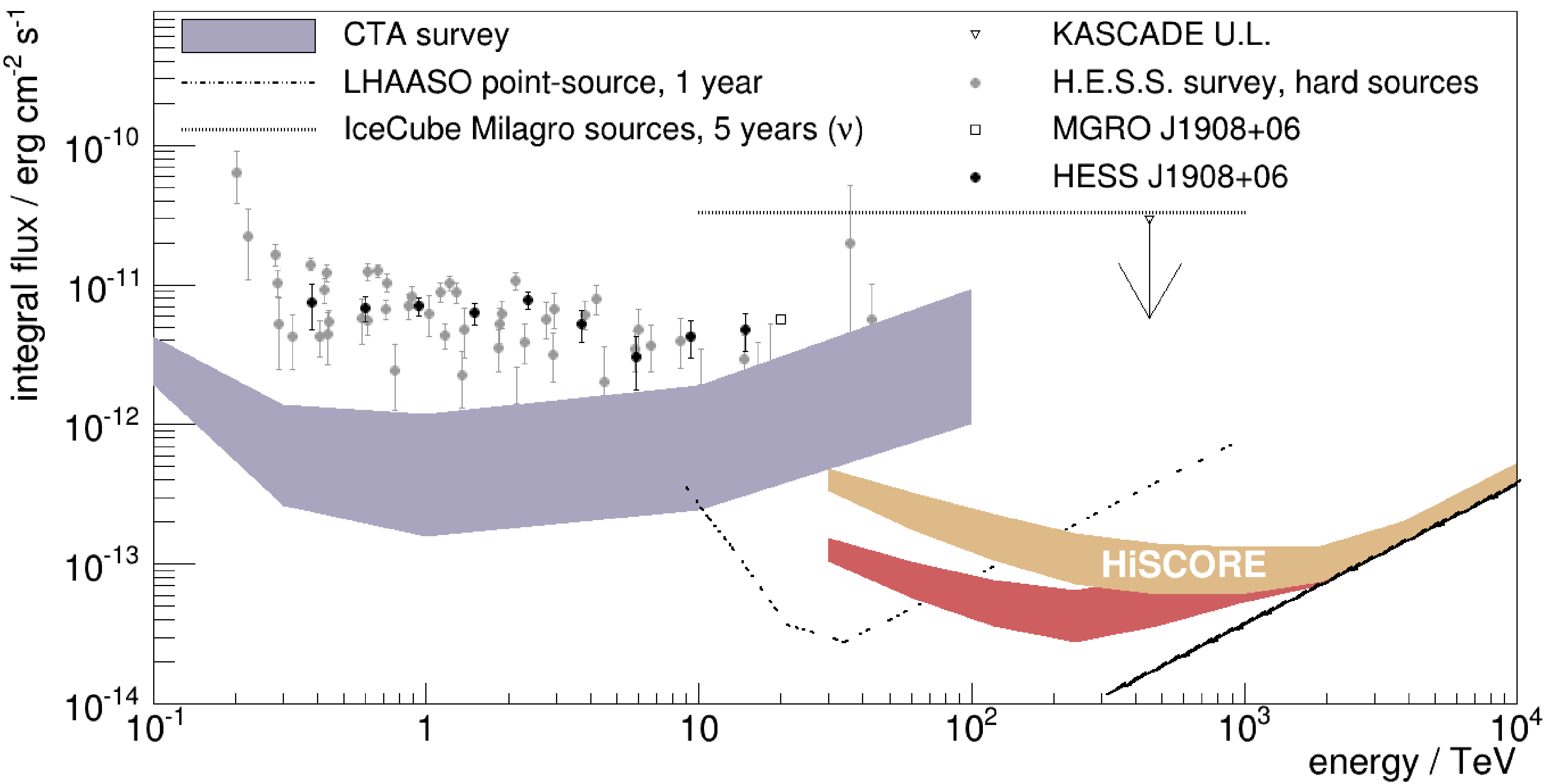
Hybrid events: Sensitivity



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Astronomy

Accessing a new energy range (E>10TeV)

- Pevatrons
- Diffuse Galactic emission
- Absorption by pair production with Interstellar photon field
  - Indirect measurement of field density
  - Distance measurement using gamma-ray spectra
- Heavy dark matter
- Unexpected discoveries...

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Summary

- **Timing information**
  - Best provided by air Cherenkov technique
  - Complementary to imaging
  - Combination with imaging promising
- **Large arrays possible with low level of complexity**
- **Potential for opening up gamma-ray astronomy in the multi-TeV regime**

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Backup slides

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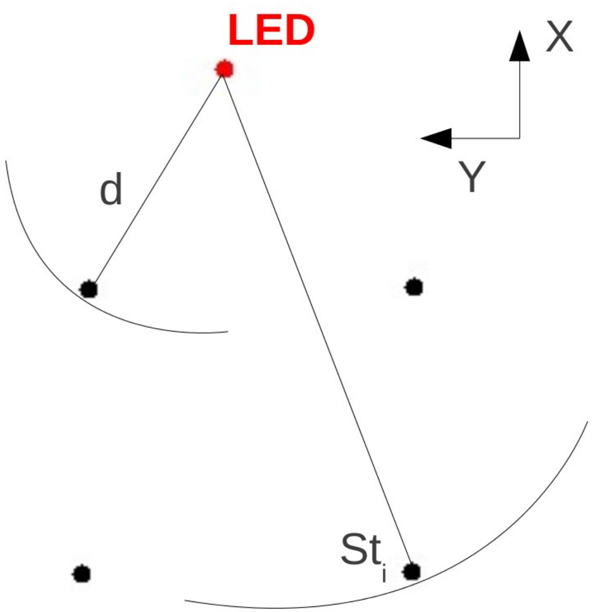
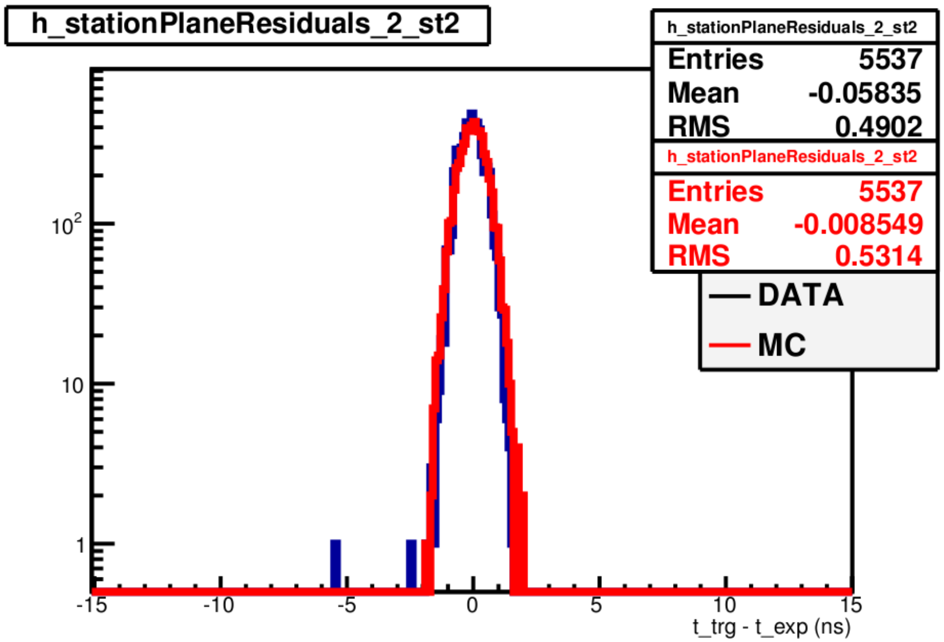
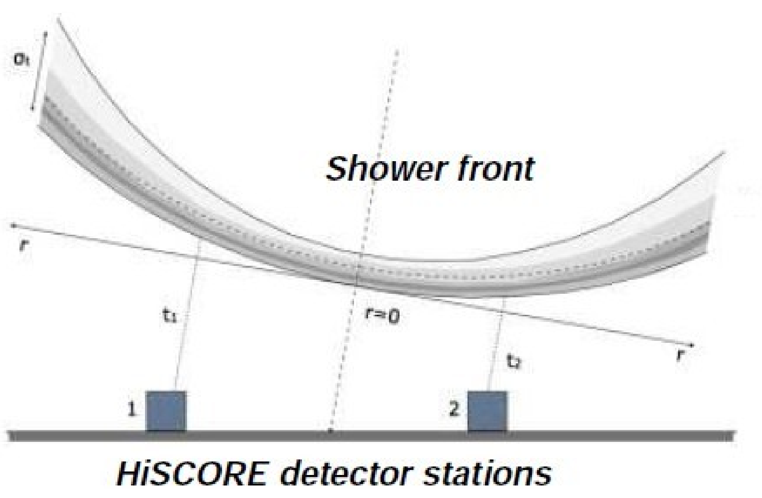
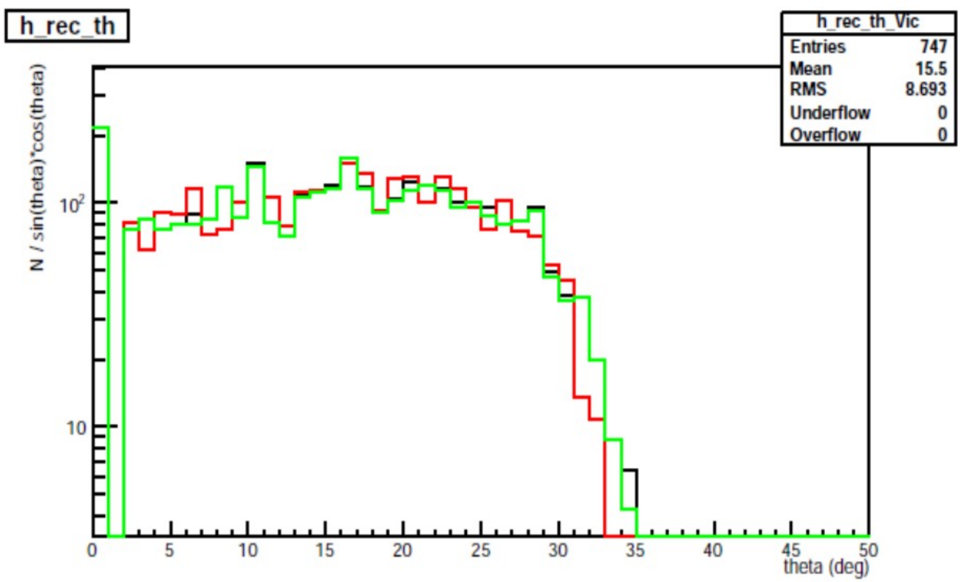
Time calibration









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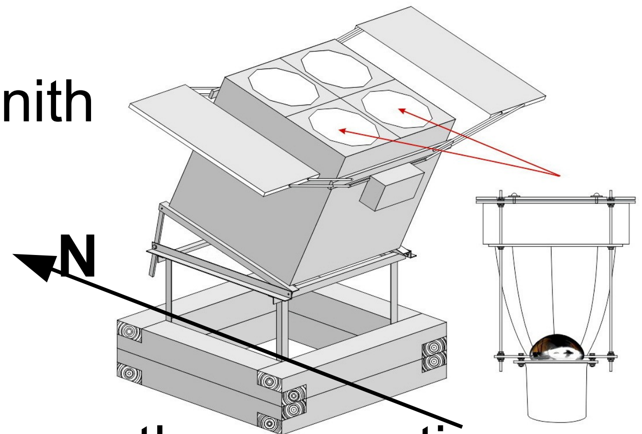
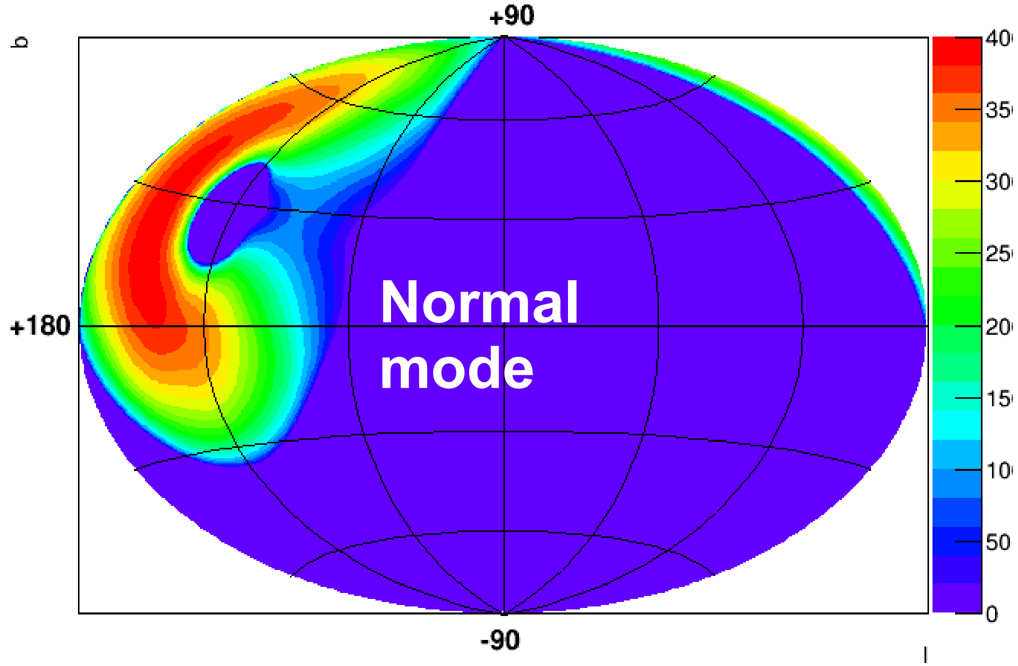
Sky coverage

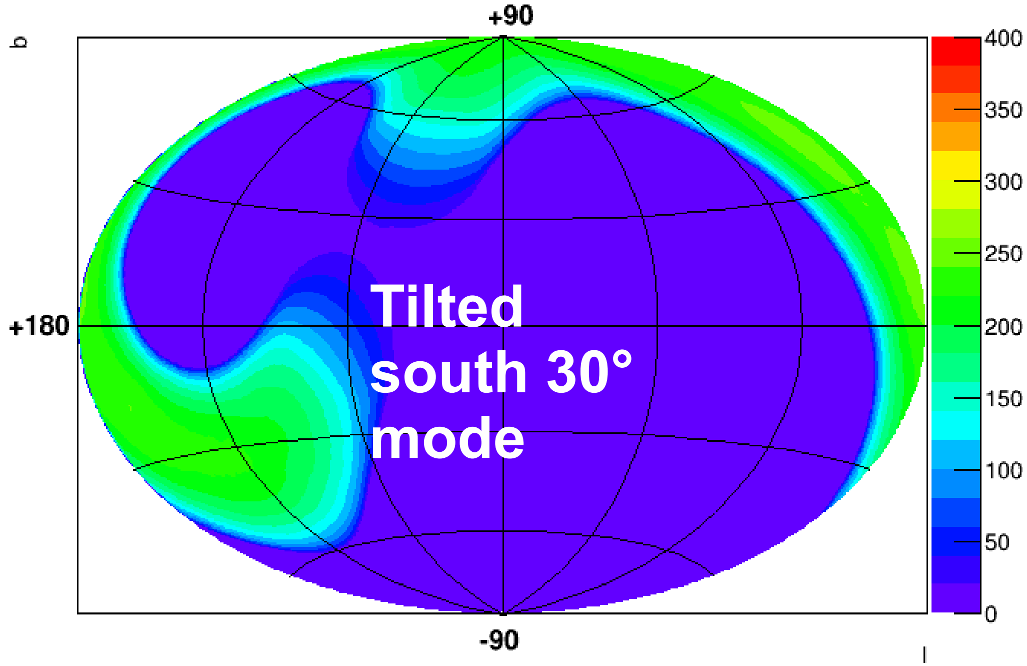
Standard observation mode: station points to zenith
Tilted mode: inclined along the north-south axis.

Tilting: coverage of different parts of the sky.



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





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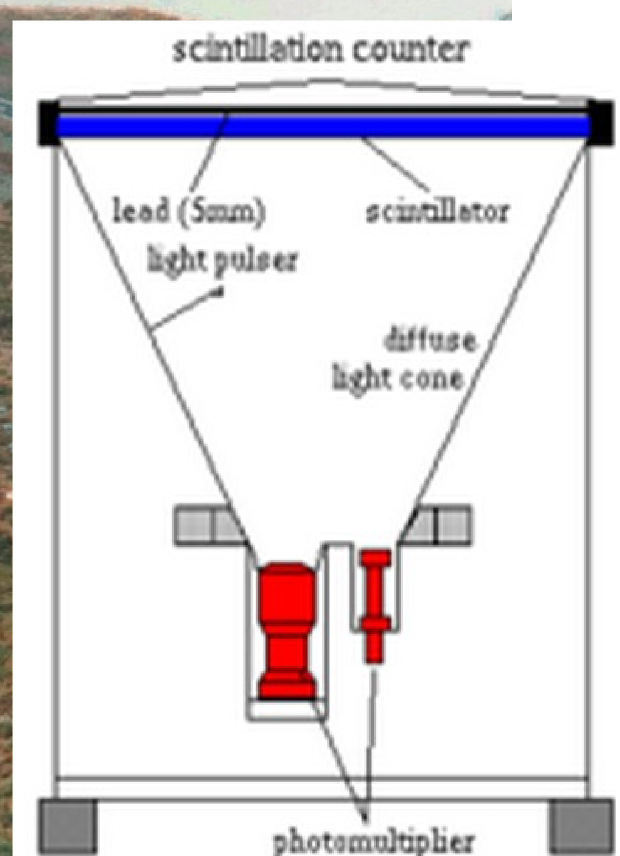
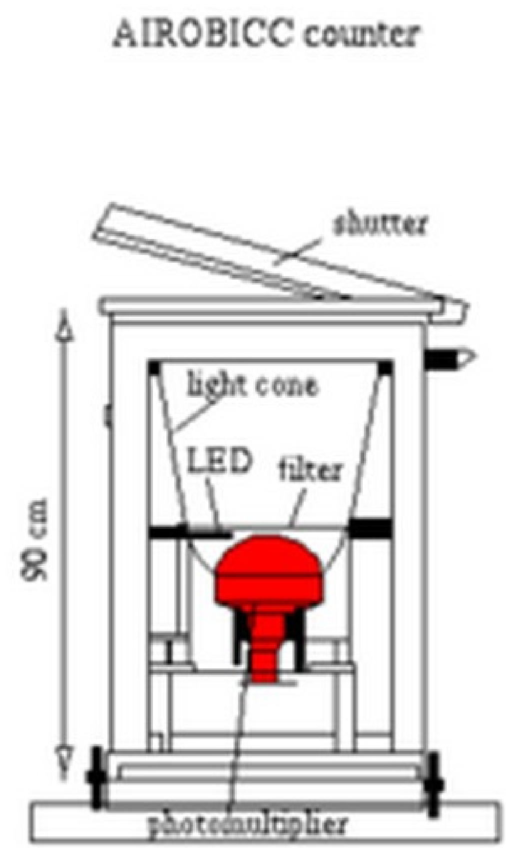
Past experiments

- Themistocle
- AIROBICC





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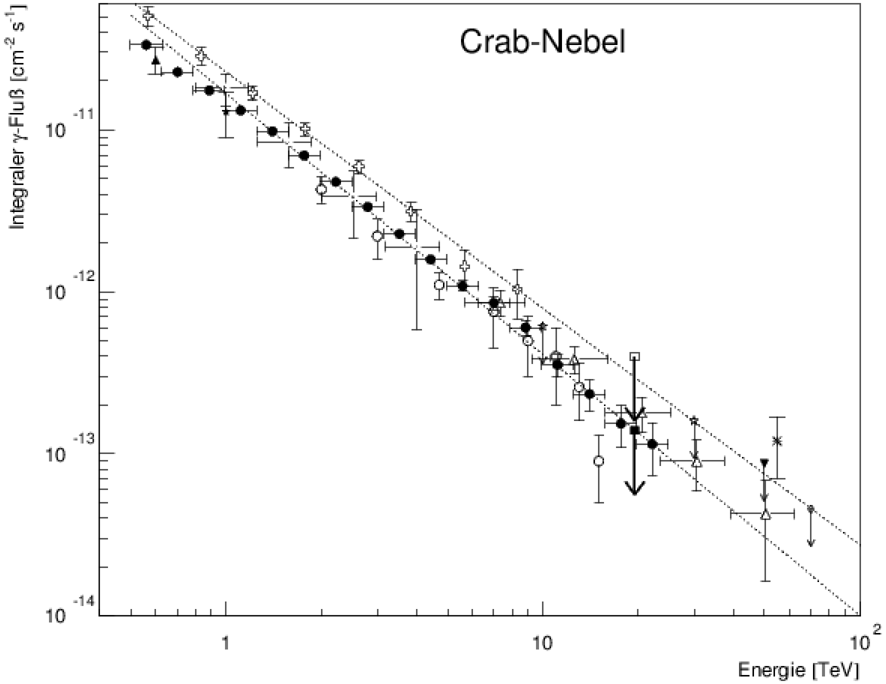
AIROBICC results



Nr.	Objekt	N_{QB}	$\hat{N}_{QB}$ $(= \alpha \cdot N_{BG})$	N_{OG}	S_{DC} $[\sigma]$	$S_{burst, exp}$ $[\sigma]$	$S_{var, kol}$ $[\sigma]$	$E_{thr, \gamma}$ [TeV]	Φ_{OG} $[10^{-13} cm^{-2} s^{-1}]$
1	GRS1915	100 (1325)	106,1 (1318,1)	13,5	**−0,57** (0,19)	−2,19	1,92	20,3	1,8
2	Cyg X-3	125 (1806)	133,3 (1739,4)	14,3	**−0,71** (1,56)	1,43	0,75	20,6	1,5
3	Geminga	114 (1128)	101,1 (1092,0)	27,6	**1,24** (1,06)	−0,25	0,07	19,4	4,1
4	AE Aqr	24 (151)	16,0 (150,2)	14,5	**1,83** (0,07)	−1,24	−0,16	27,0	7,8
5	Berk 87	162 (2017)	142,2 (1885,2)	36,8	**1,60** (2,95)	−0,77	−1,93	20,4	3,6
6	SS433	81 (852)	79,6 (832,9)	16,0	**0,16** (0,65)	1,66	−0,25	22,8	2,3
7	Cyg X-1	137 (1907)	138,5 (1914,0)	18,7	**−0,11** (−0,15)	−0,17	−0,36	20,1	1,9
8	Her X-1	156 (1624)	117,4 (1602,5)	54,9	**3,33** (0,53)	1,35	1,13	20,3	6,5
9	AM Her	98 (1149)	89,9 (1127,8)	22,3	**0,82** (0,62)	1,33	1,10	22,8	2,8
10	V404 Cyg	137 (1989)	140,2 (1966,7)	17,8	**−0,25** (0,49)	−2,00	0,21	20,1	1,8

Hybrid events: more reconstruction

- Expect sensitivity boost:
  - Scaled width cut and timing hadron rejection (Q~3)
  - Further g/h separation: Angular cut, length, …
    (+ more sophisticated methods)
  - Improved angular resolution from hybrid events: e.g. treat telescope as part of array (not yet simulated)
  - Consider time-development of image → independent direction reconstruction

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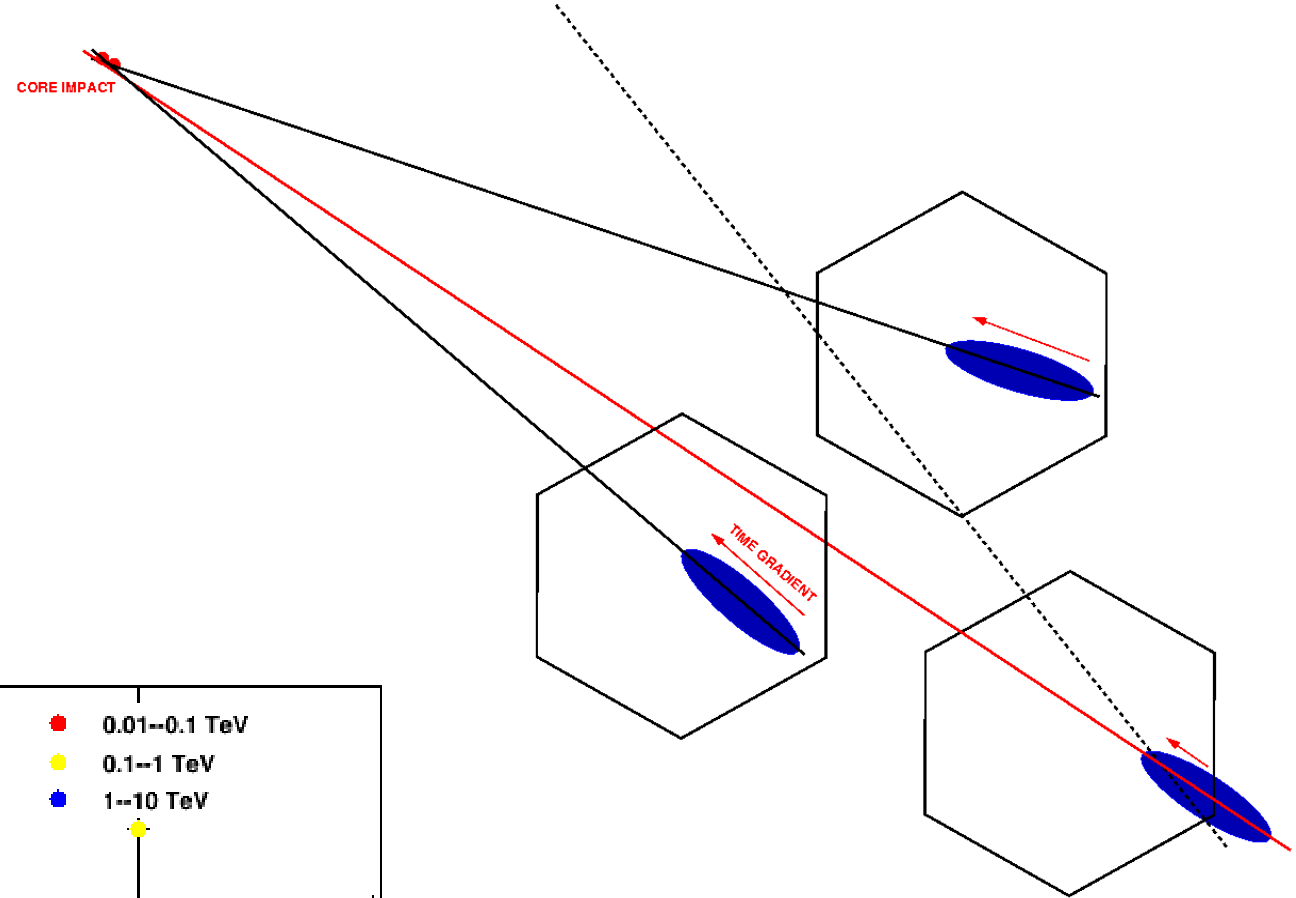
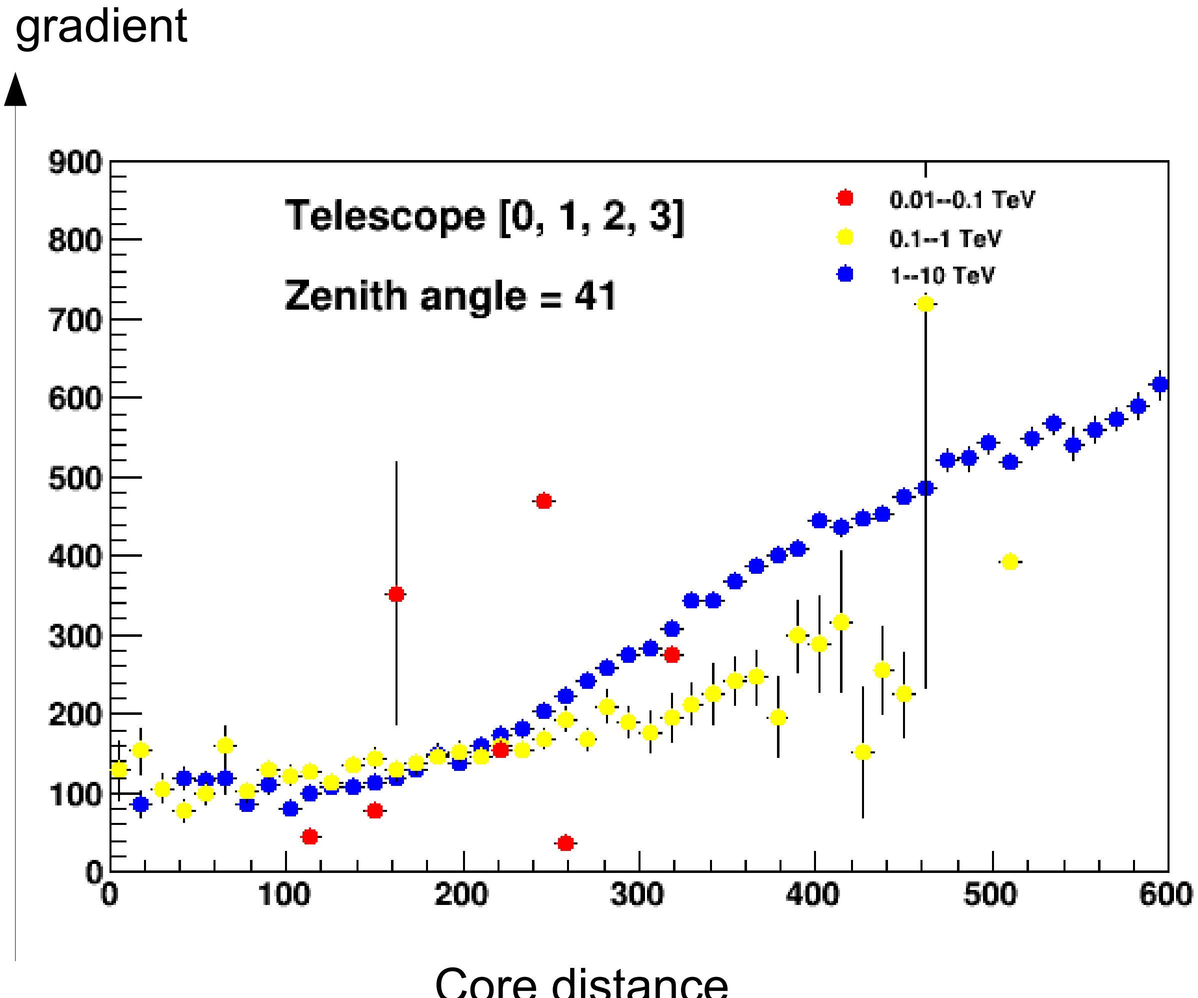
Large zenith angle: outside HiSCORE viewcone





sim_telarray simulation, 2010

Test width scaling with IACT+HiSCORE "toy-MC-test"

- Full simulation sim_telarray
- 2D-lookup-table for MC-width w_{MC}(core, size)
- MC-core **randomized** with HiSCORE resolution
- Use randomized core position for width scaling

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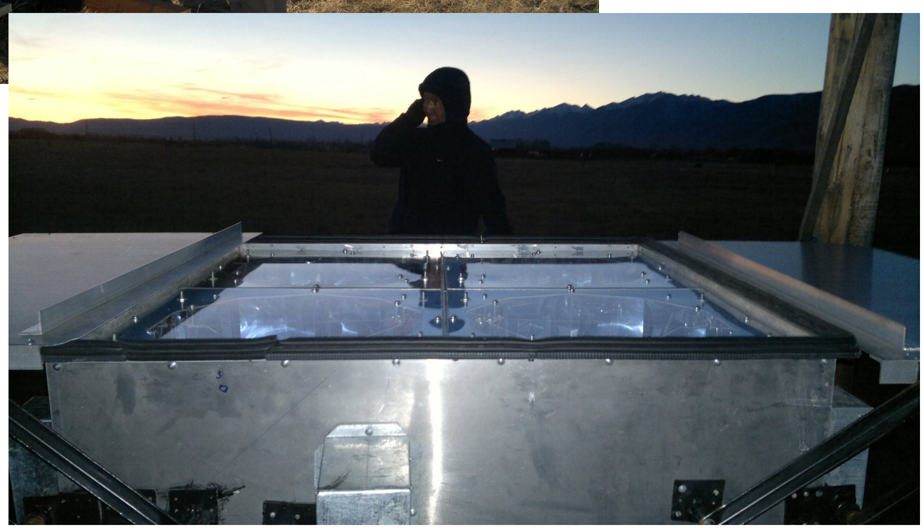
Tunka HiSCORE Status

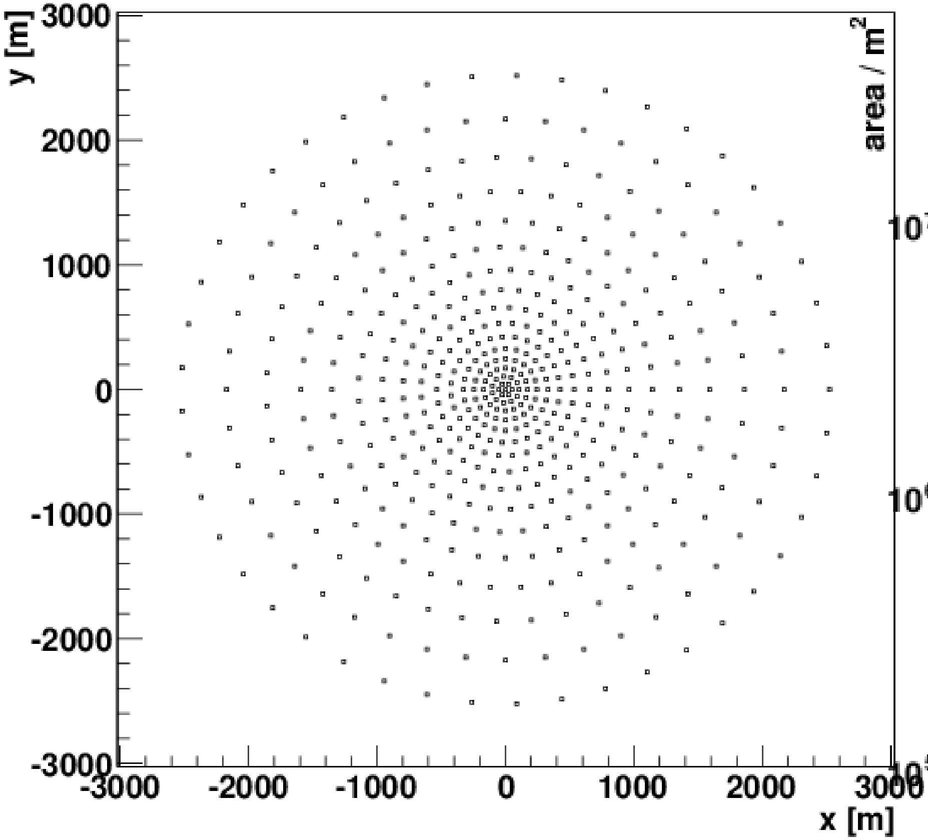
Optical station

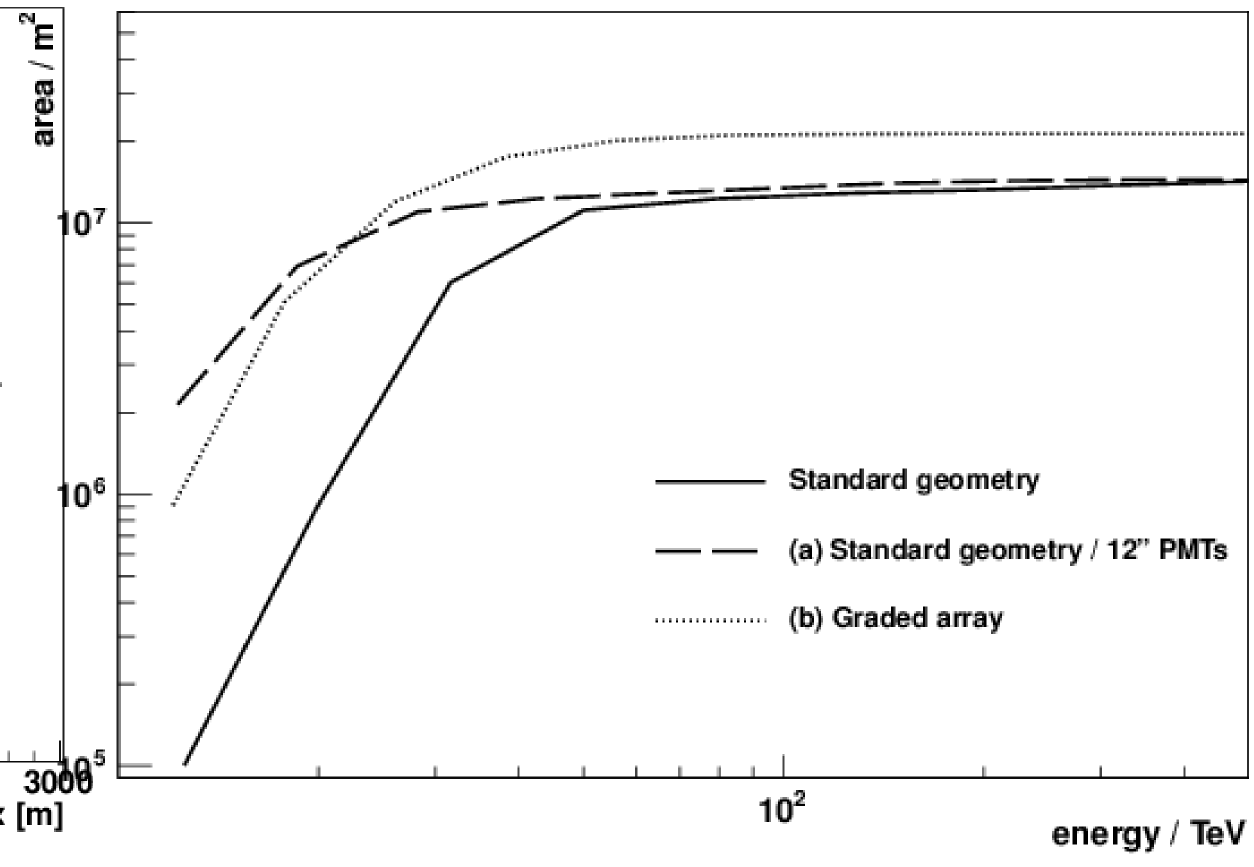
Electronic box



Array Optimization HiSCORE

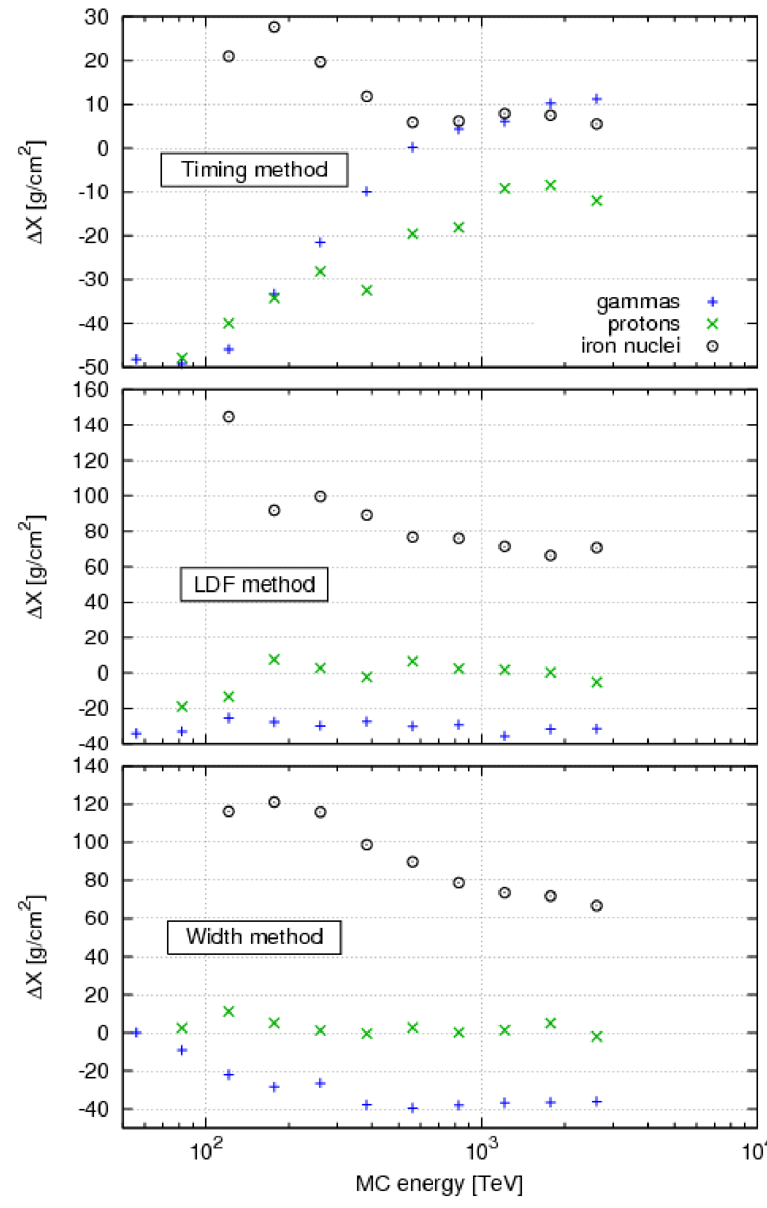
Simulation studies:
→ Large PMTs (12")
→ Graded array layout





Gamma-hadron separation

Systematic bias



- LDF & widths : sensitive to whole shower
  Large overestimation for heavy particles
  (long tails)

- Timing : sensitive to specific point
  (edge time)
  Small overestimation for heavy particles

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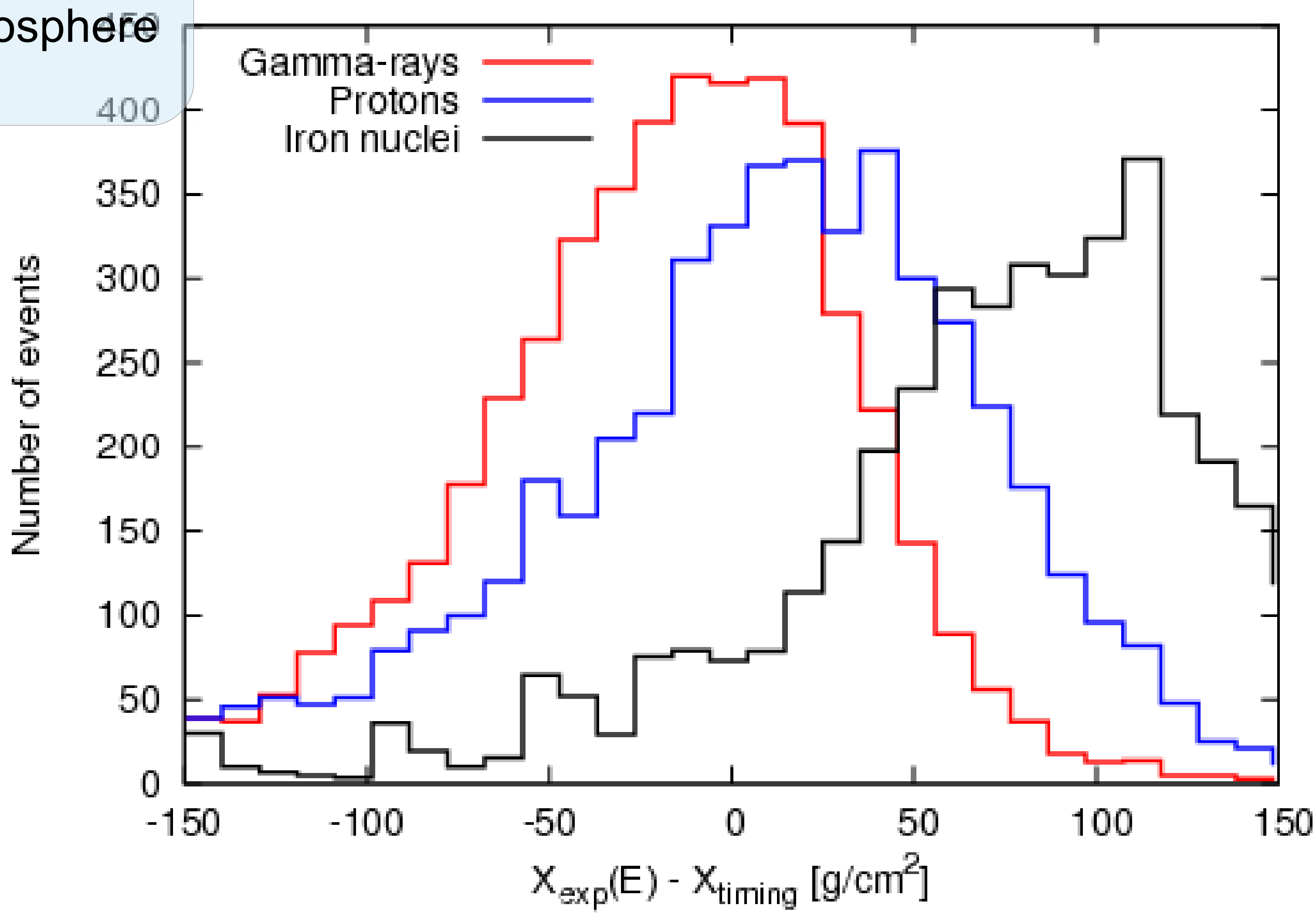
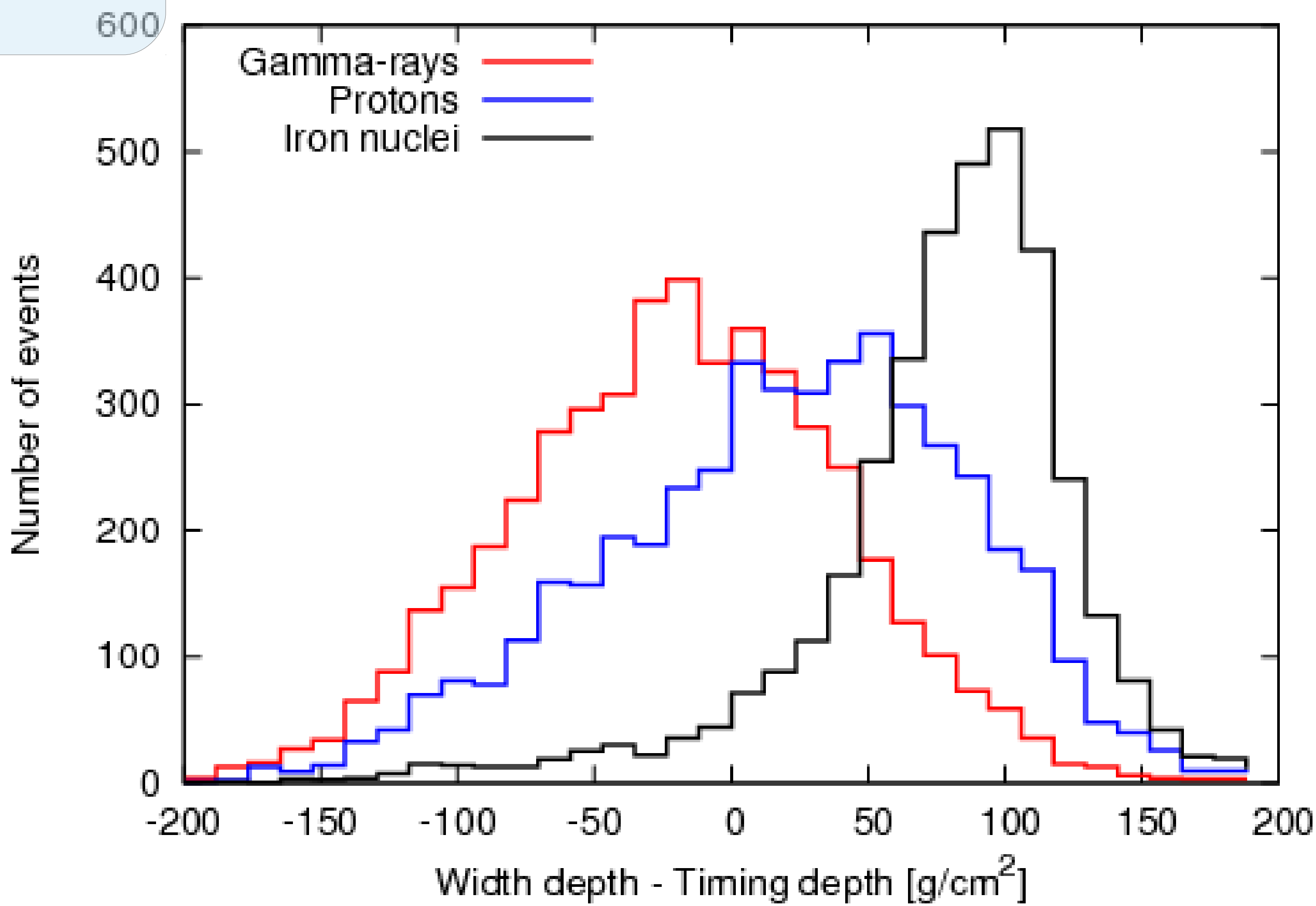
Particle separation

Lighter particles develop
Higher up in atmosphere

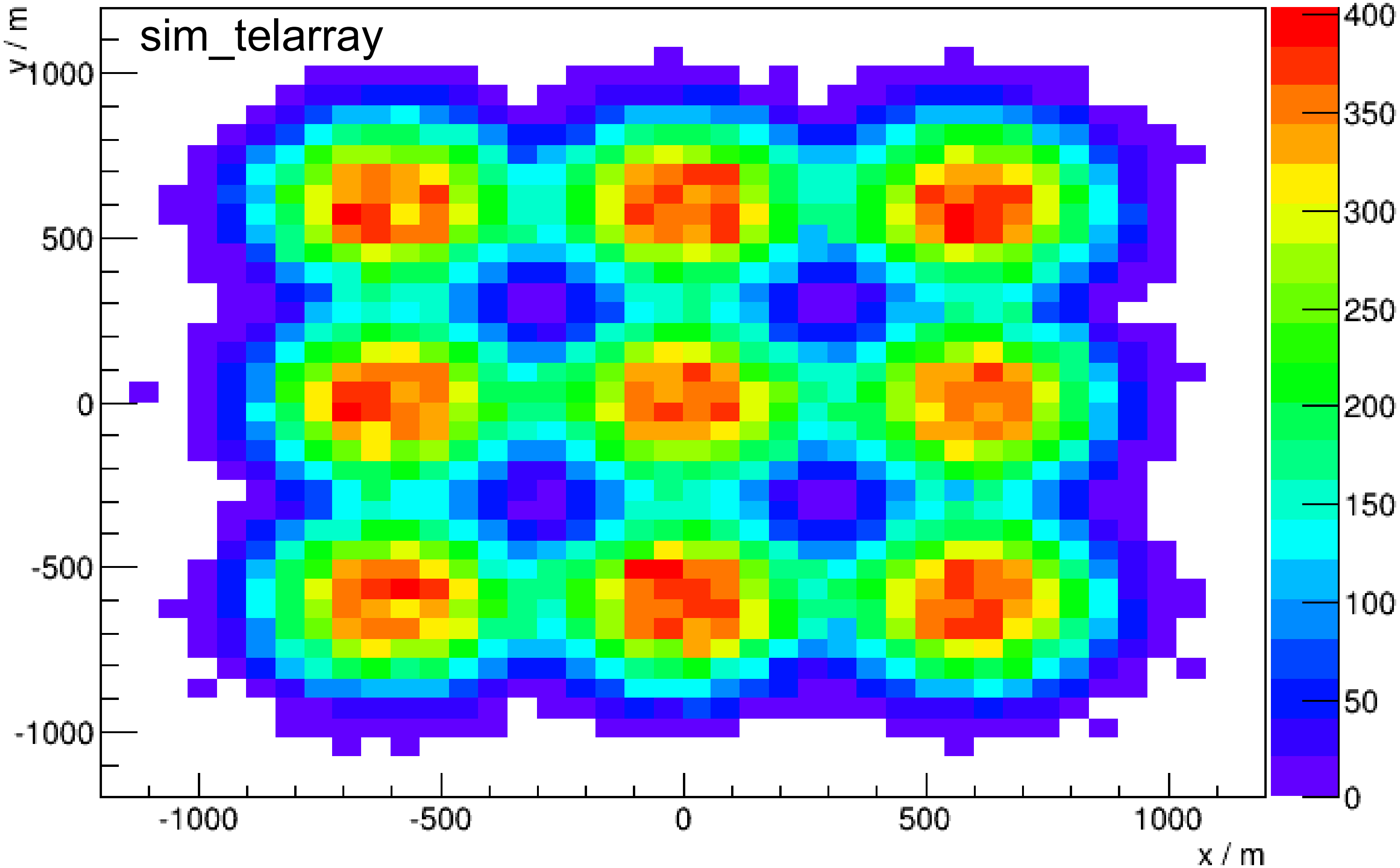


Particle separation (2)

Systematic Xmax difference
Time width and timing model

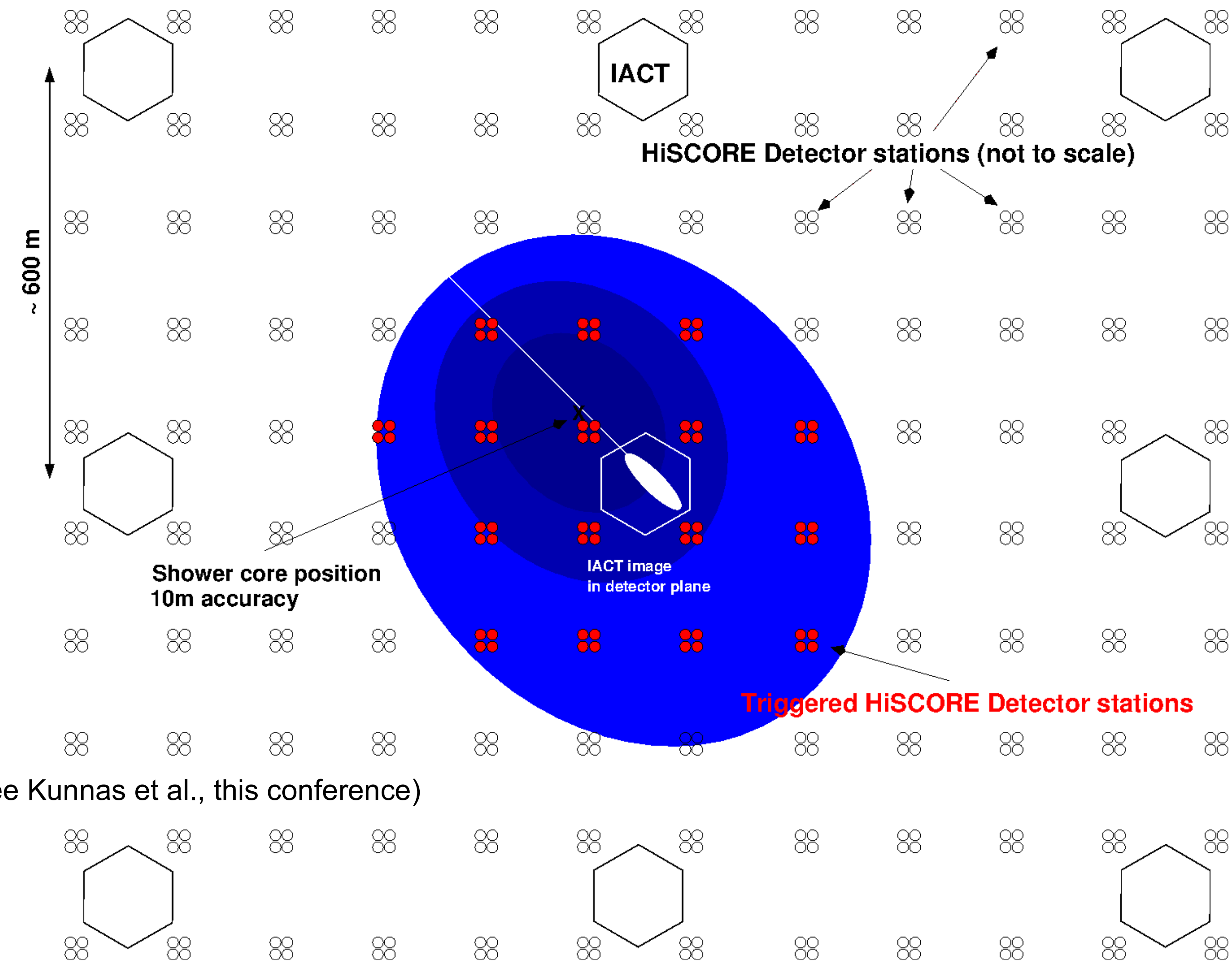


HiSCORE + IACTs



Timing array + imaging telescopes

Central reconstruction parameter: Shower core position



(also see Kunnas et al., this conference)

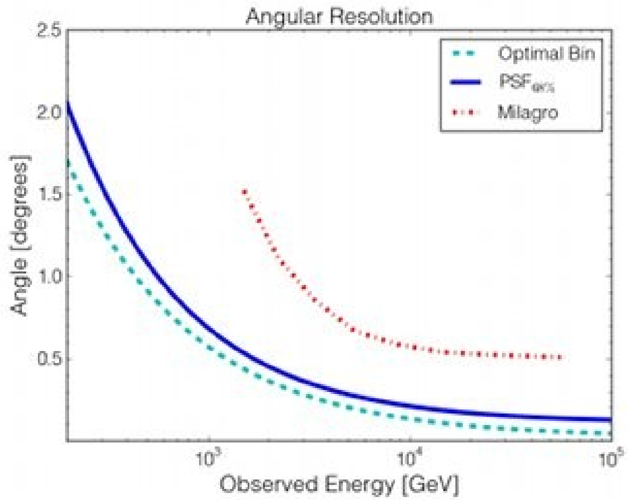
IACT image scaling using **array core position**

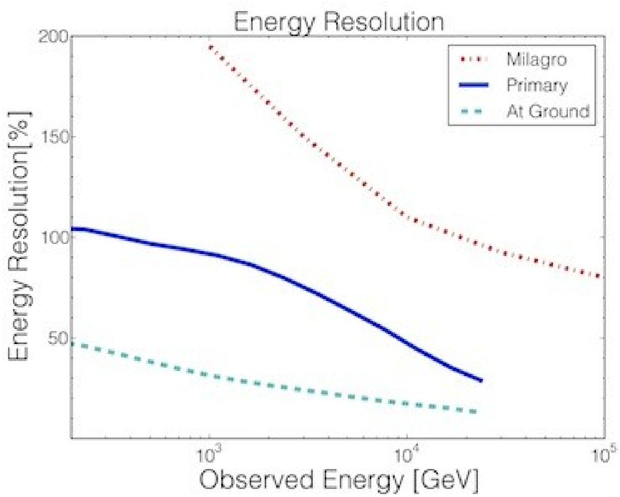
Monoscopic operation with larger distances btw telescopes

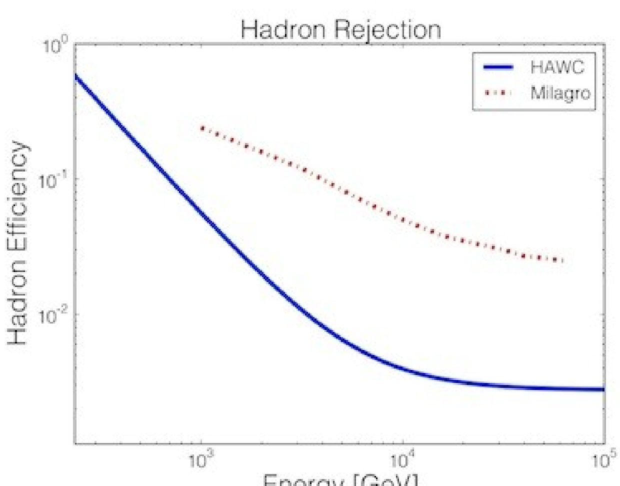
Increased area / telescope; Hybrid event reconstruction

improvement of g/h separation x2-3

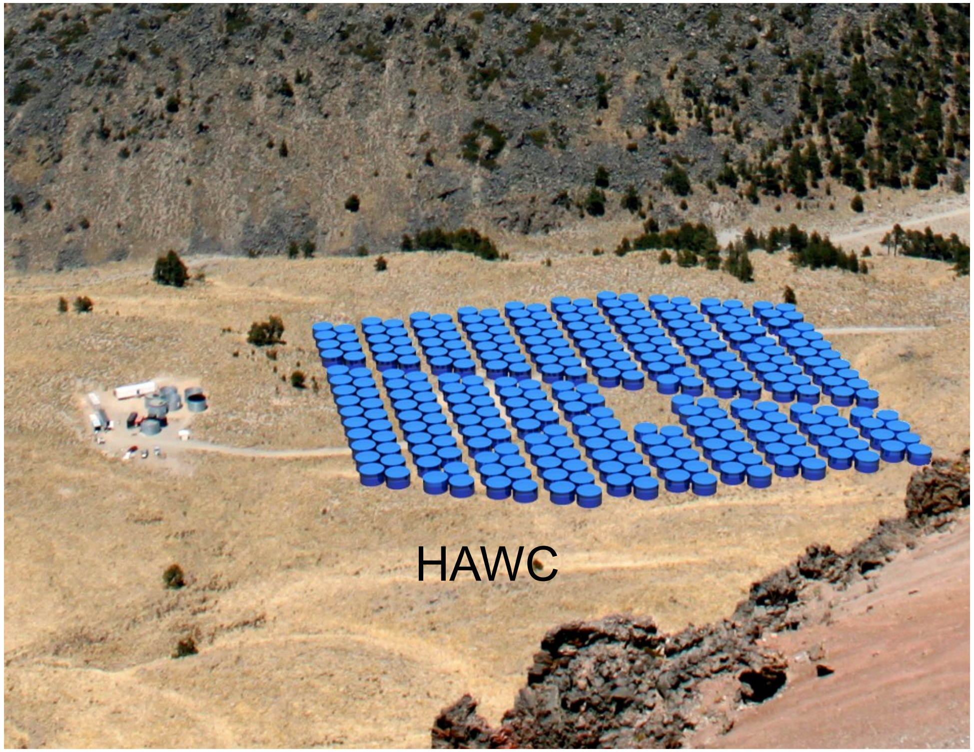
Milagro / HAWC







http://umdgrb.umd.edu/~bbaugh/work/hawc.php



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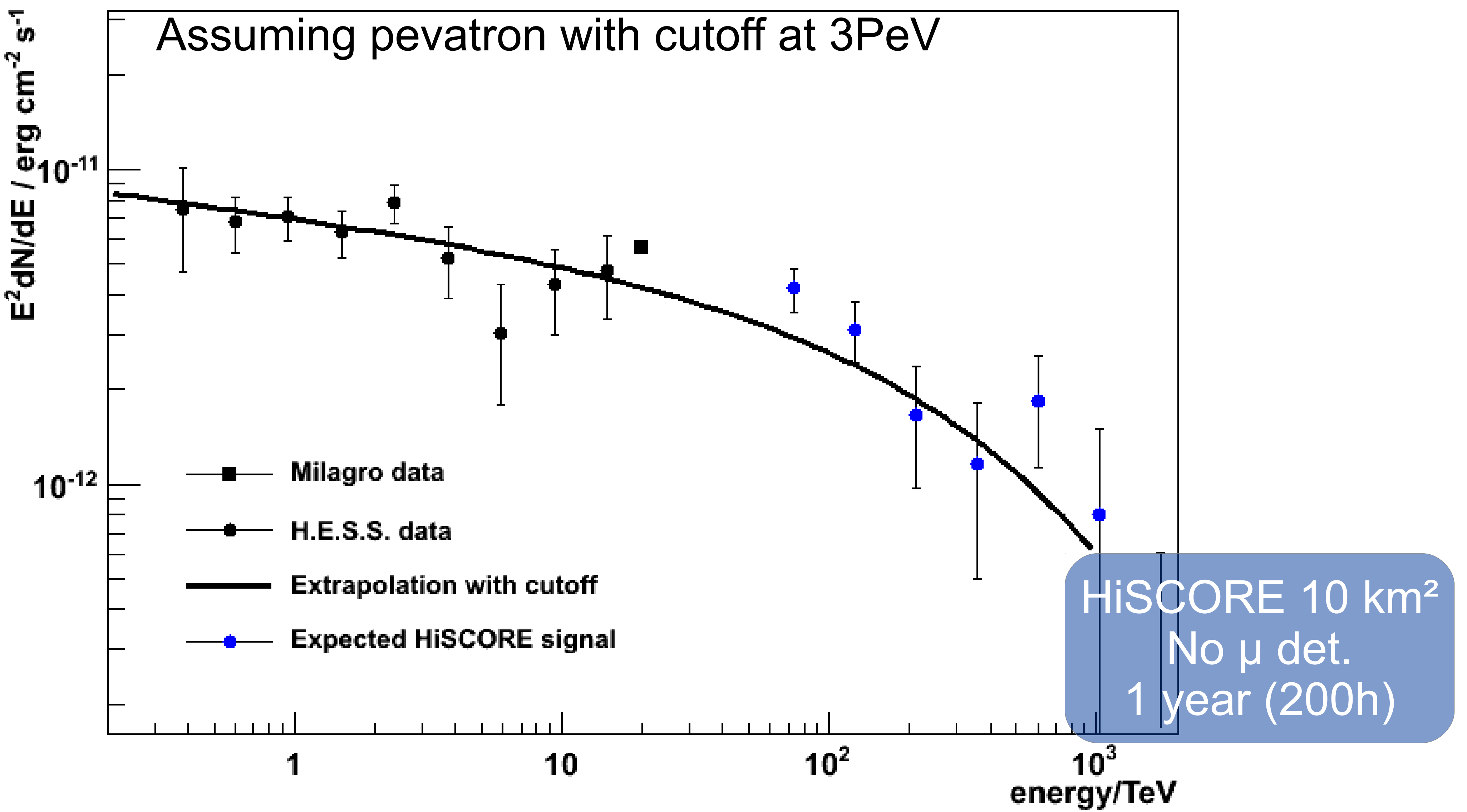
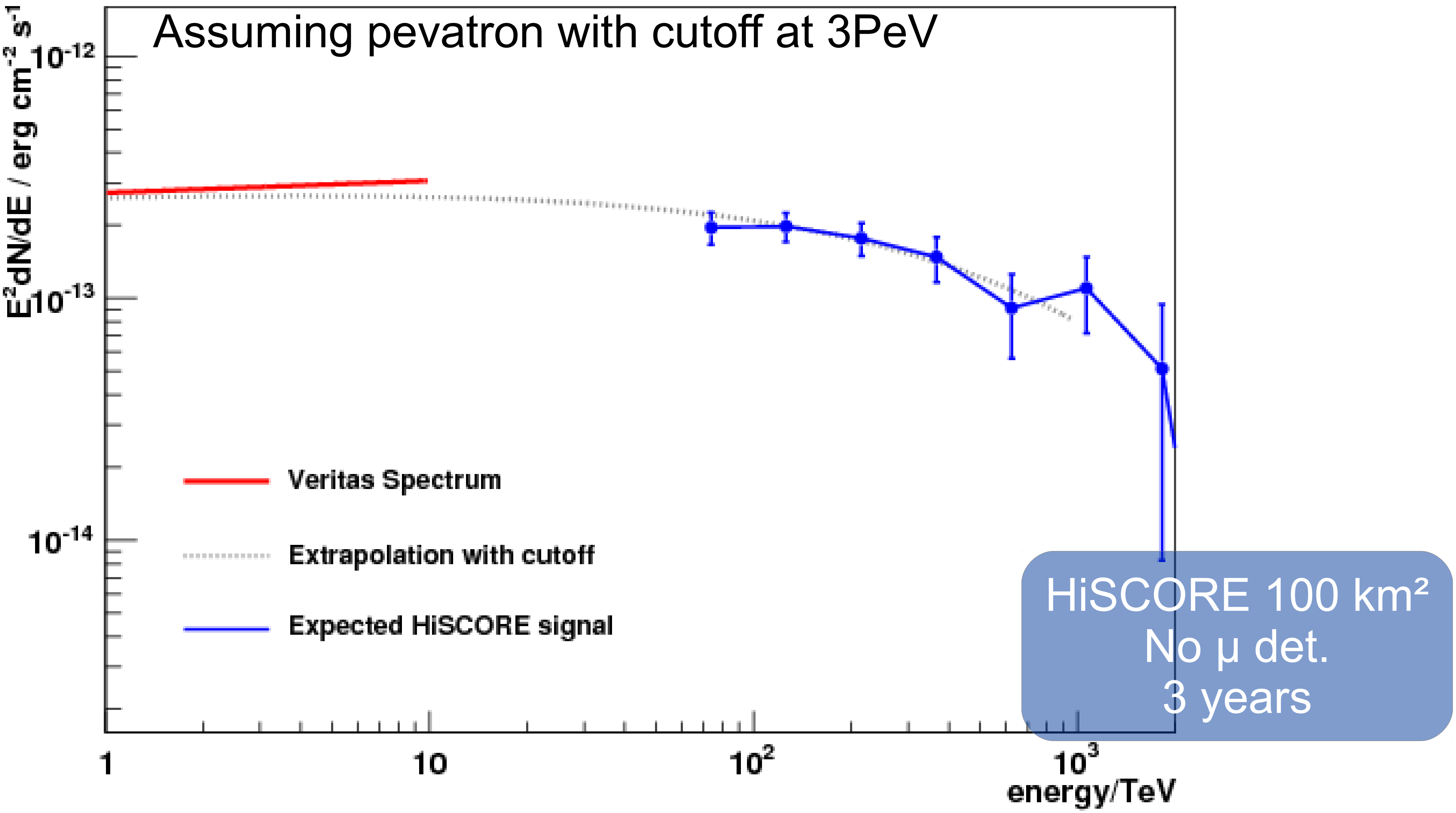
MGRO J1908+06



Tycho Supernova remnant



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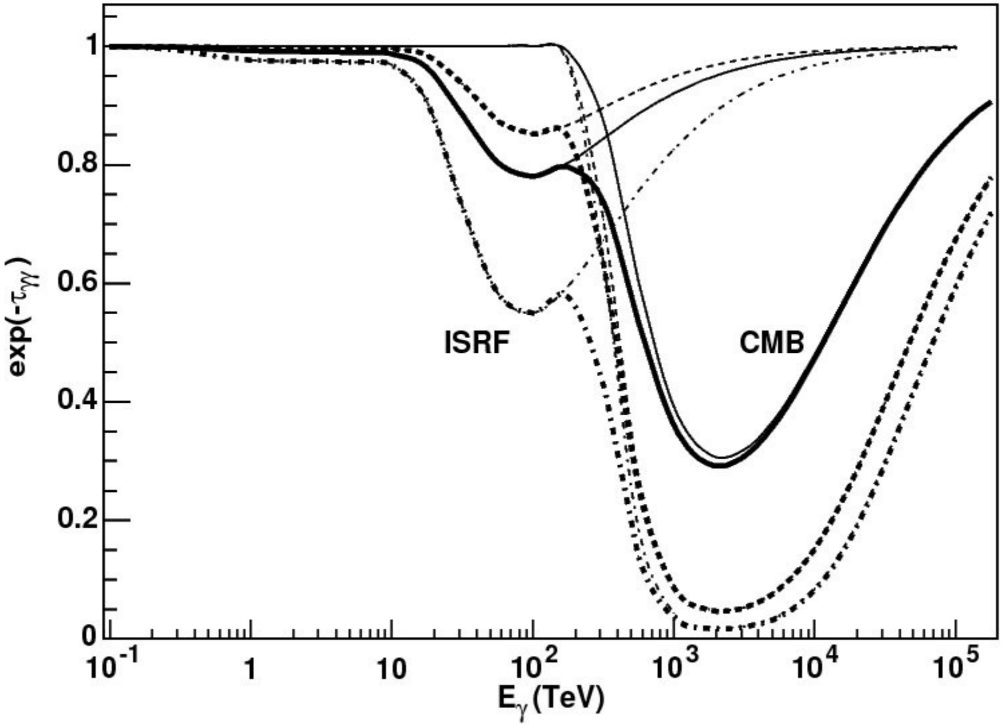
Absorption

Galaxy: 100TeV-PeV: e+e-pair production with low-E photons

- **Interstellar radiation field**
- **Cosmic Microwave Background**

(e.g. Moskalenko et al. 2006)



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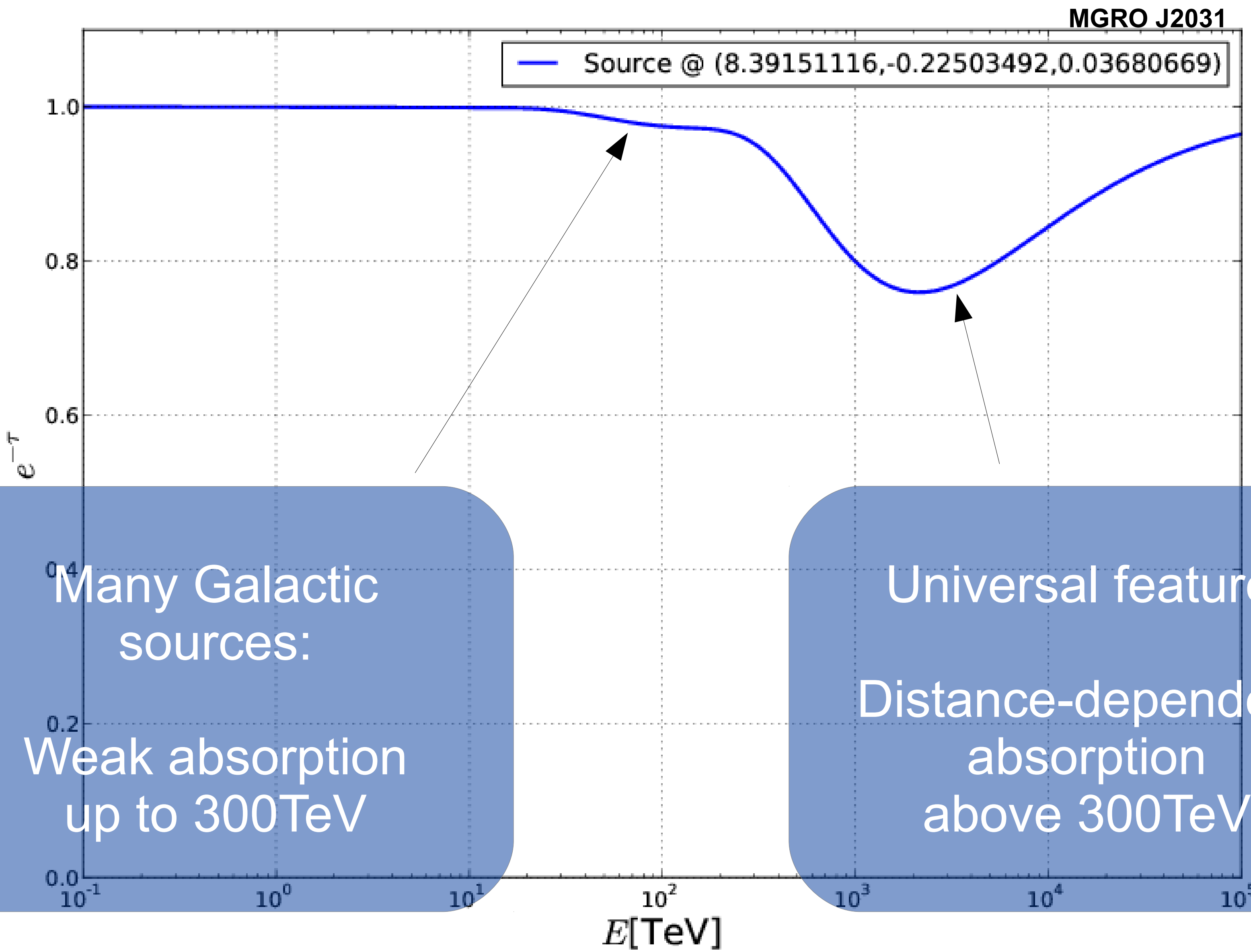
Absorption



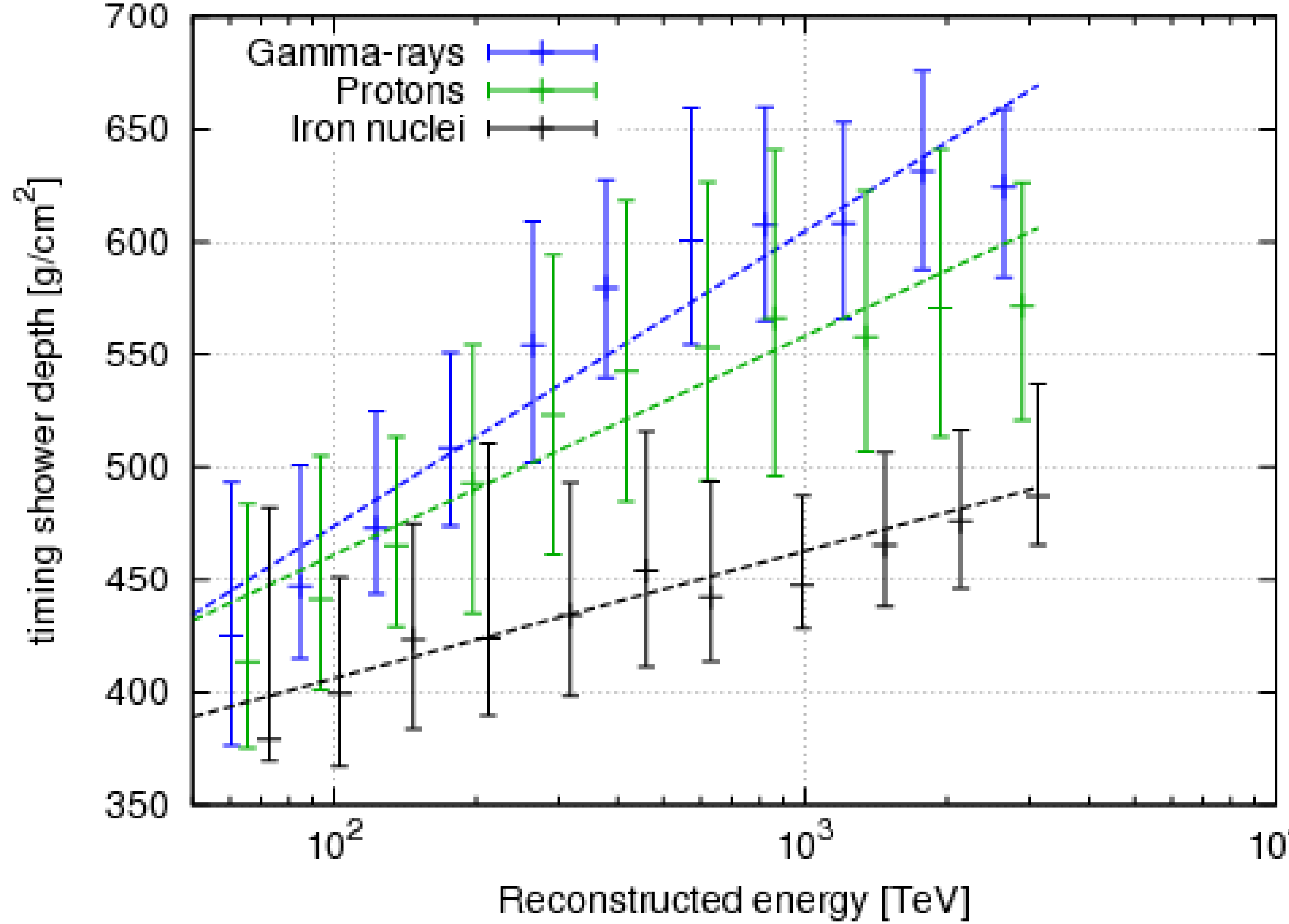
Many Galactic sources:

Weak absorption up to 300TeV

Universal feature:

Distance-dependent absorption above 300TeV

Particle separation Xmax vs. E



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