Multi-TeV to PeV Gamma Ray Astronomy

Motivation and Strategies

Martin Tluczykont

The Future of Research on Cosmic Gamma Rays, La Palma, August 2015

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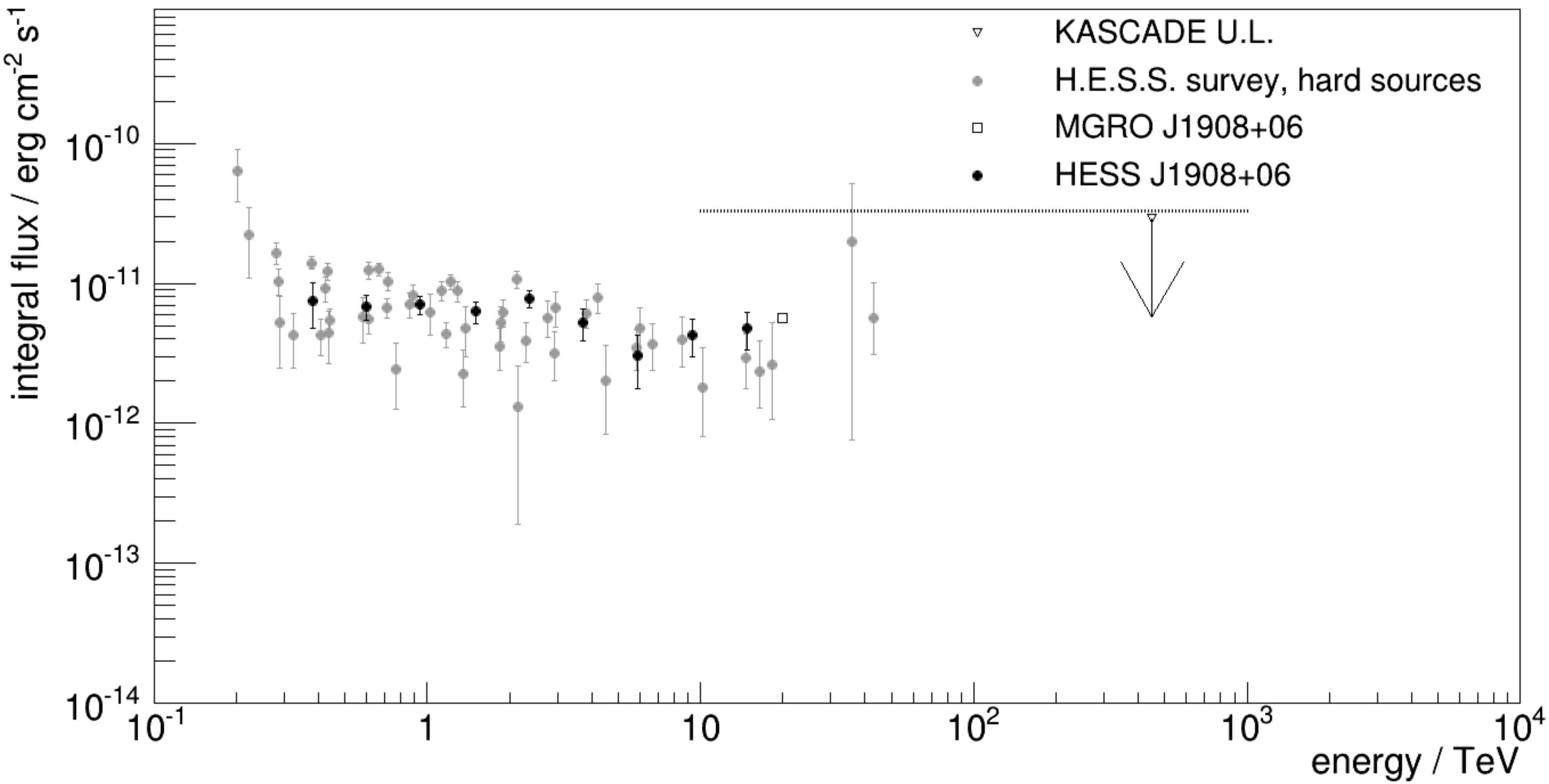
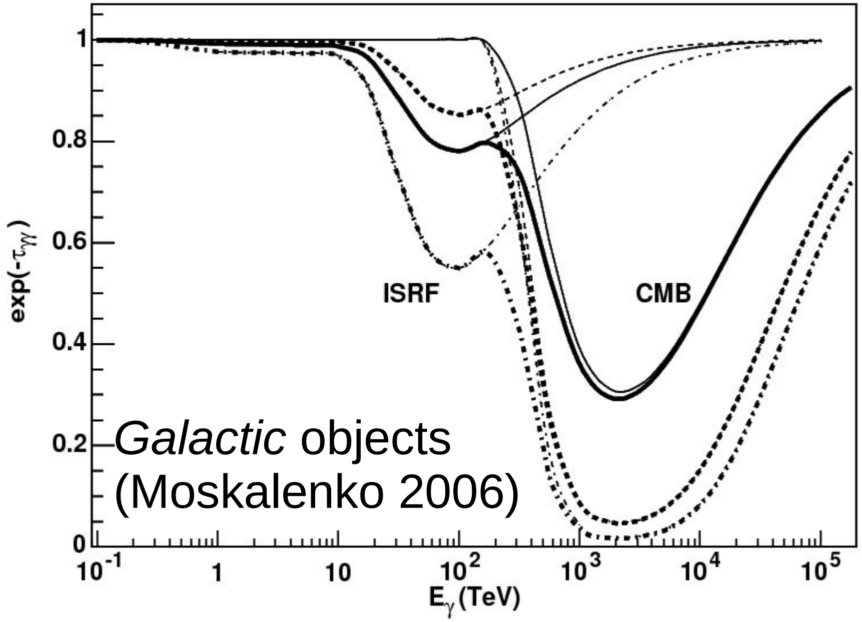
VHE-UHE Gamma-ray astronomy

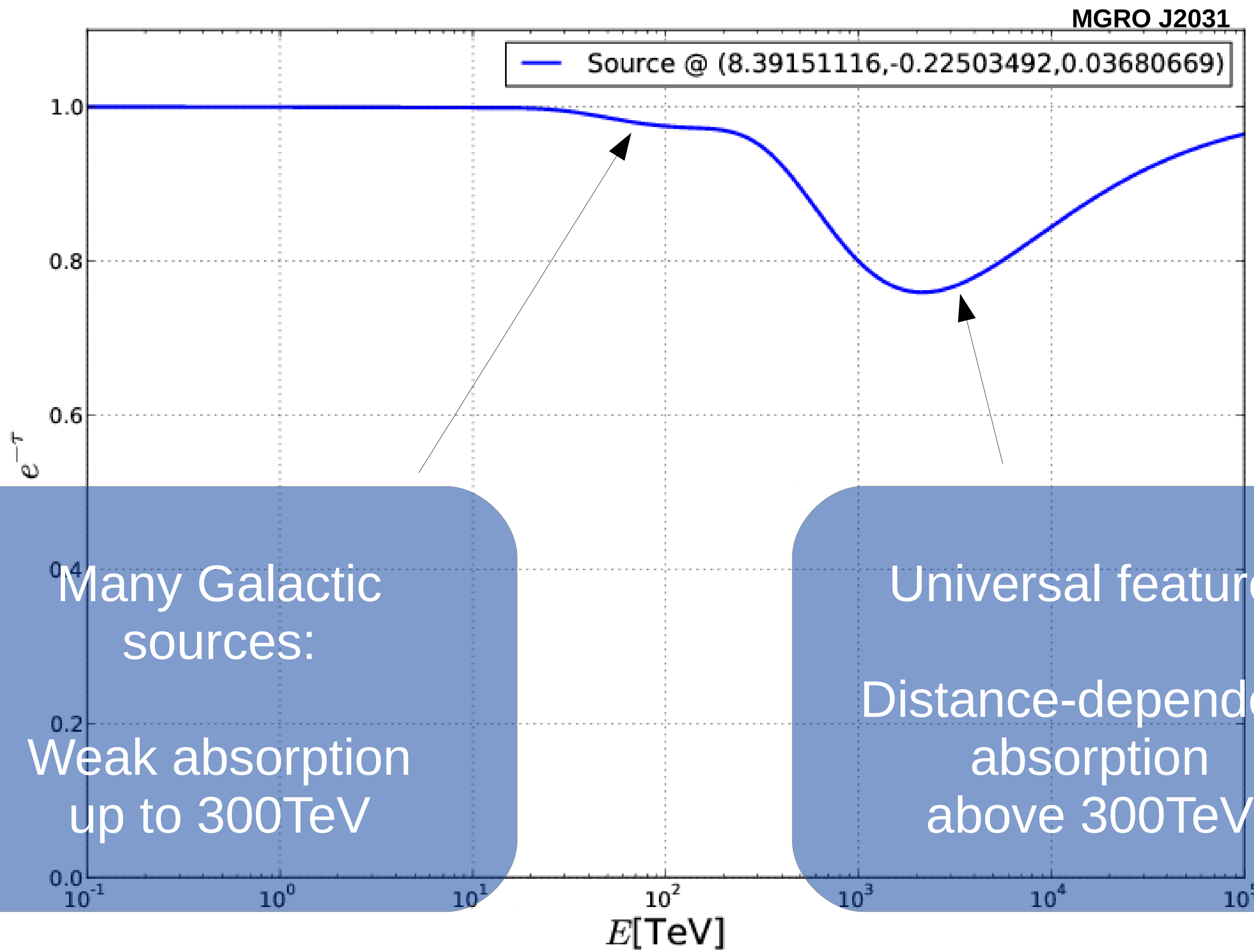


Multi-TeV to PeV Gamma rays

- No hadronic/leptonic ambiguity:
  - IC: Klein-Nishina regime → steep spectra
  - Pi° decay: hard spectra possible
- Absorption e+e-:
  - 20+TeV: Mid- to far-infrared region of EBL (*Extragalactic*)
  - 100 TeV: ISRF (*Galactic*)
  - 3 PeV: CMB (*Galactic*)



Absorption (e^+e^-), Galactic



A. Maurer

Many Galactic sources:

Weak absorption up to 300TeV

Universal feature:

Distance-dependent absorption above 300TeV

Pevatrons

- Galactic cosmic rays up to knee:
  Gamma-rays up to few 100 TeV → Pevatrons
- Most energetic particles released first
  - PeV C.R. only for a short period of time
  - “Delayed multi-TeV signals” from clouds
  - Use clouds for C.R. acceleration mapping

Gabici & Aharonian 2007

- Recent motivation:
  H.E.S.S. Galactic center, IceCube Neutrinos

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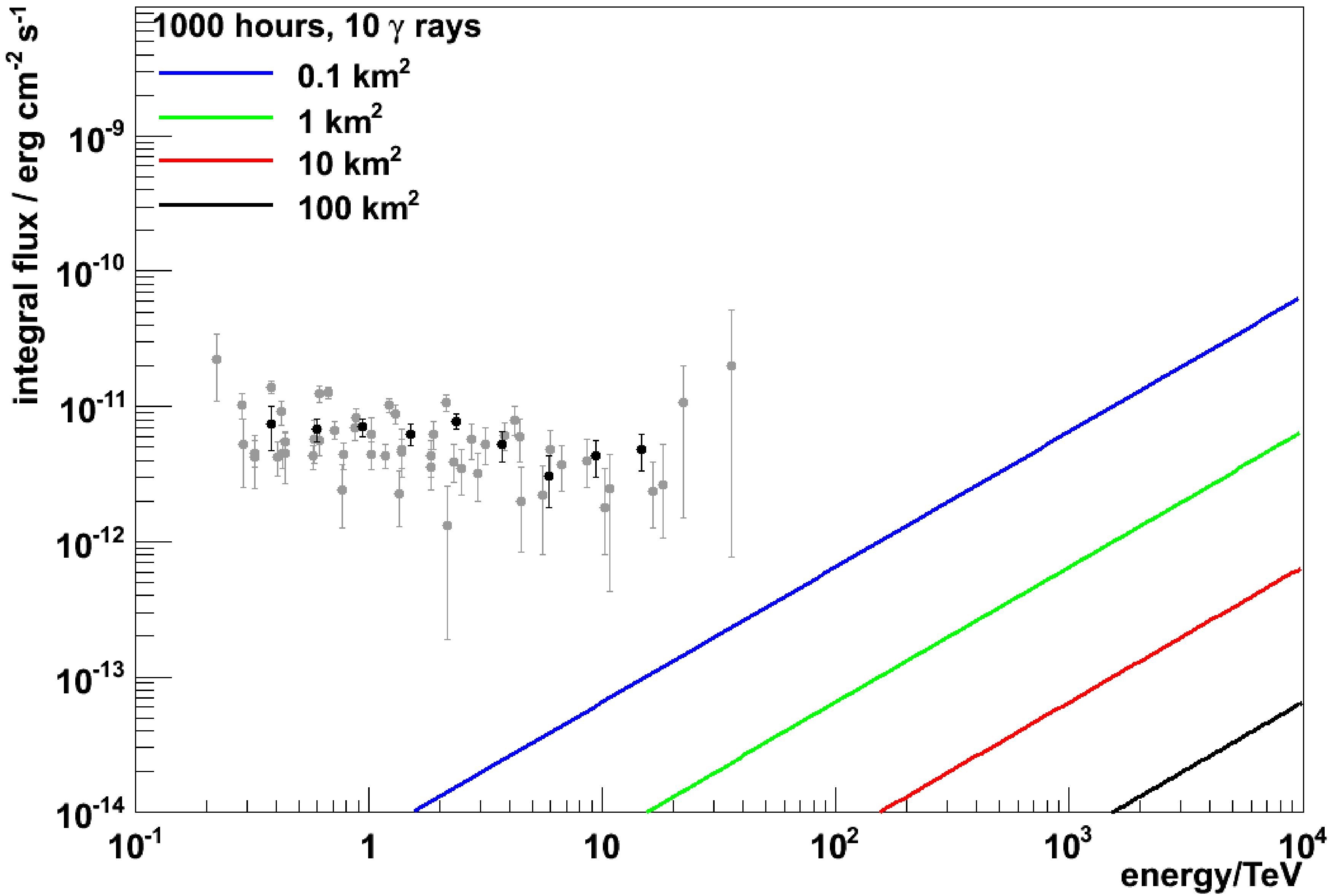
Key to Multi-TeV—PeV : Large area



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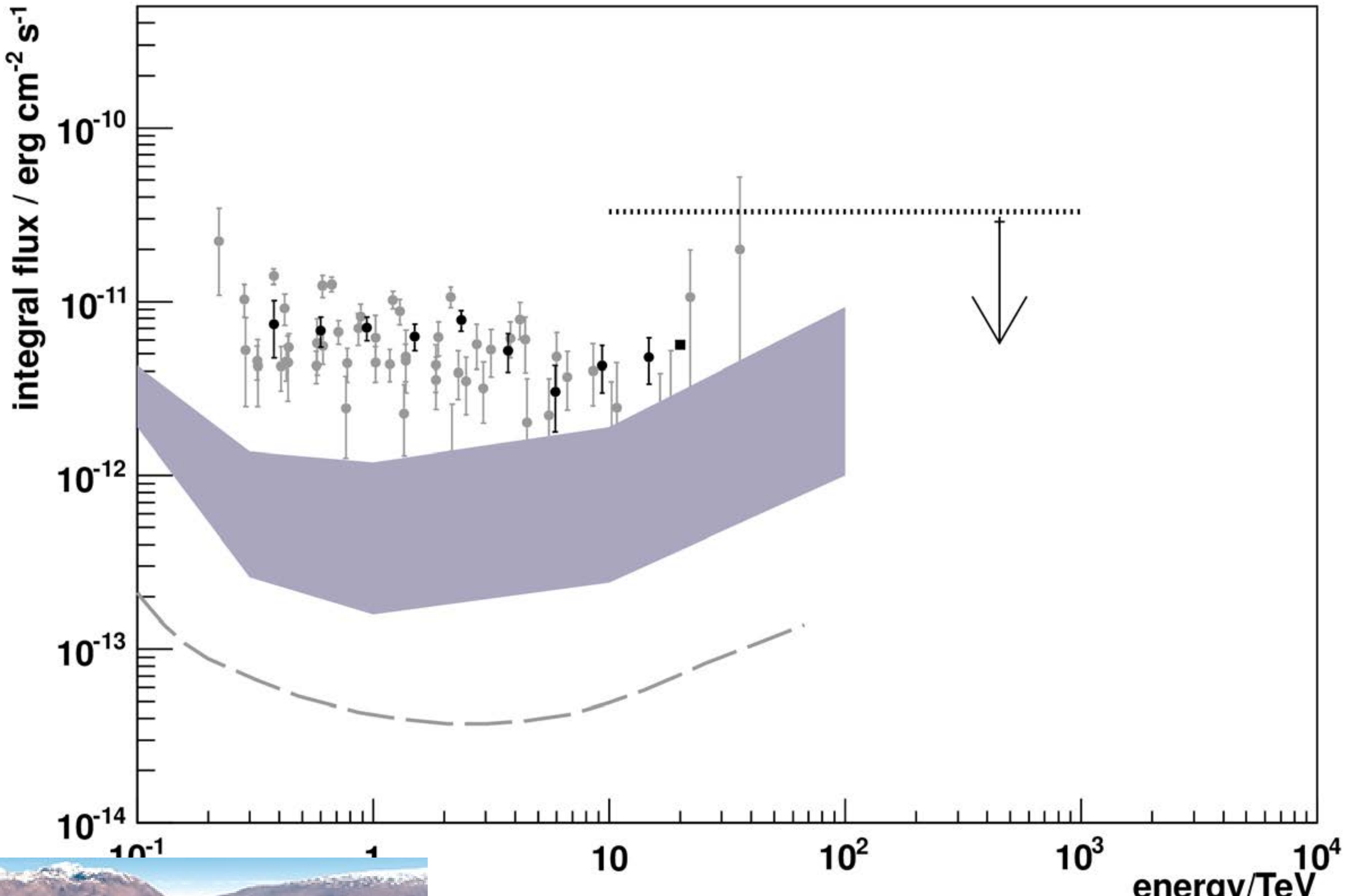
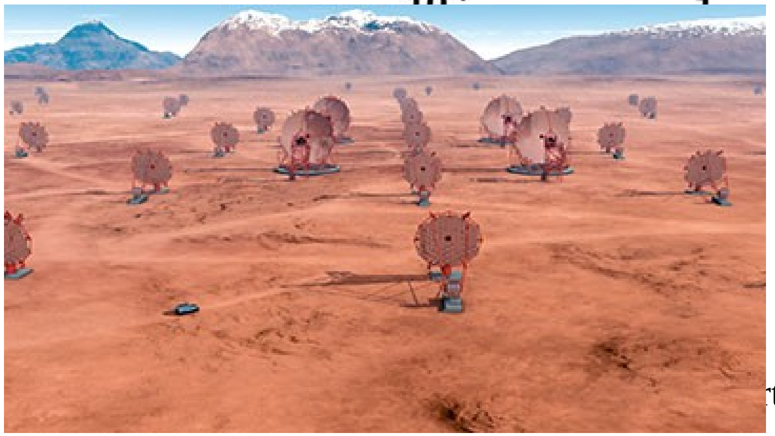
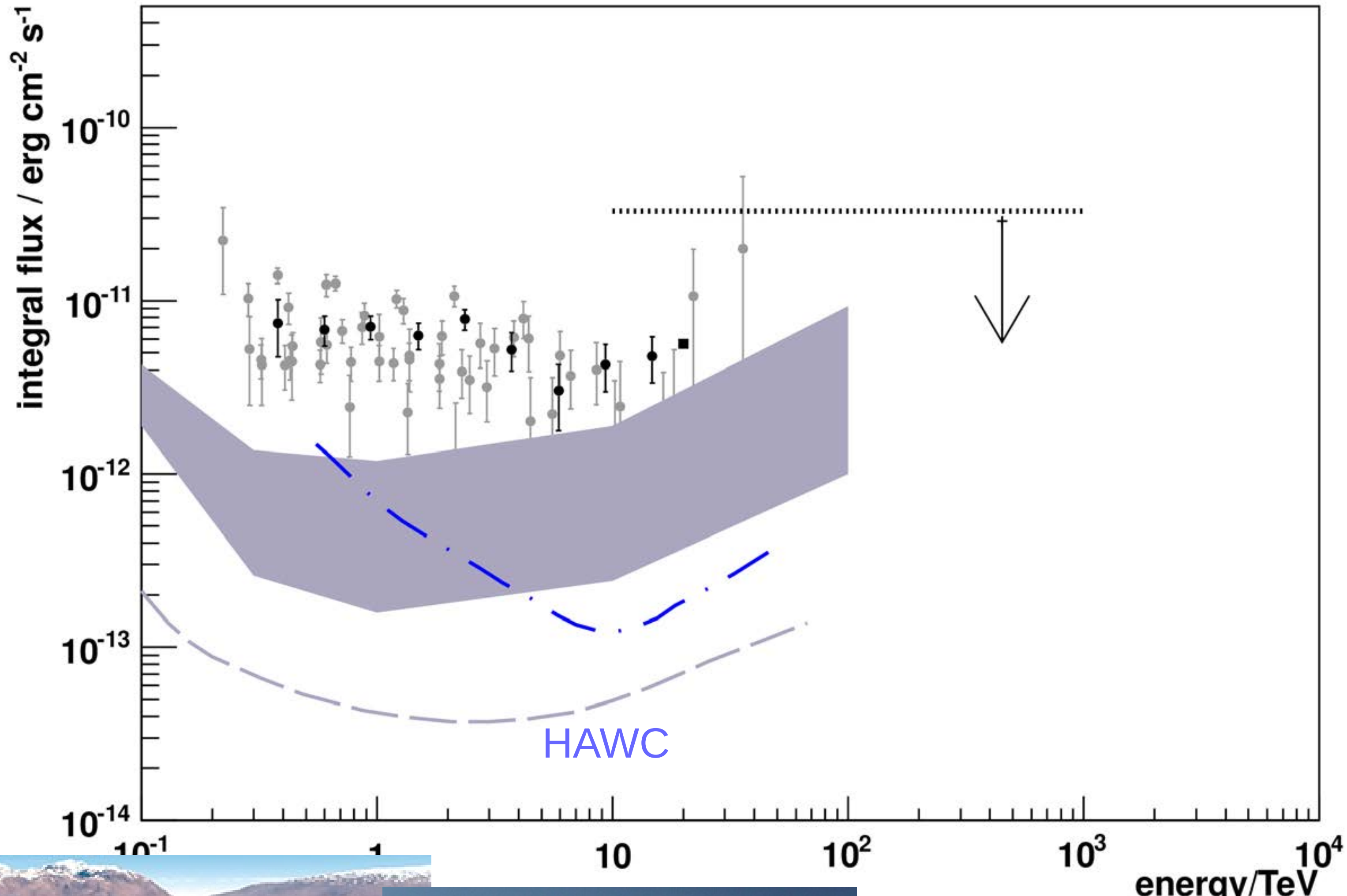
CTA

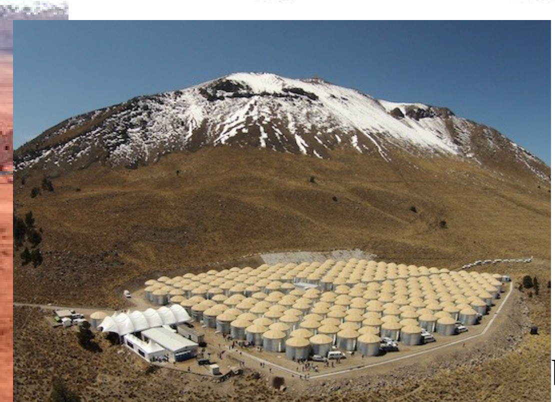




See Friday: Knödelseder, Chaves, Brown

HAWC





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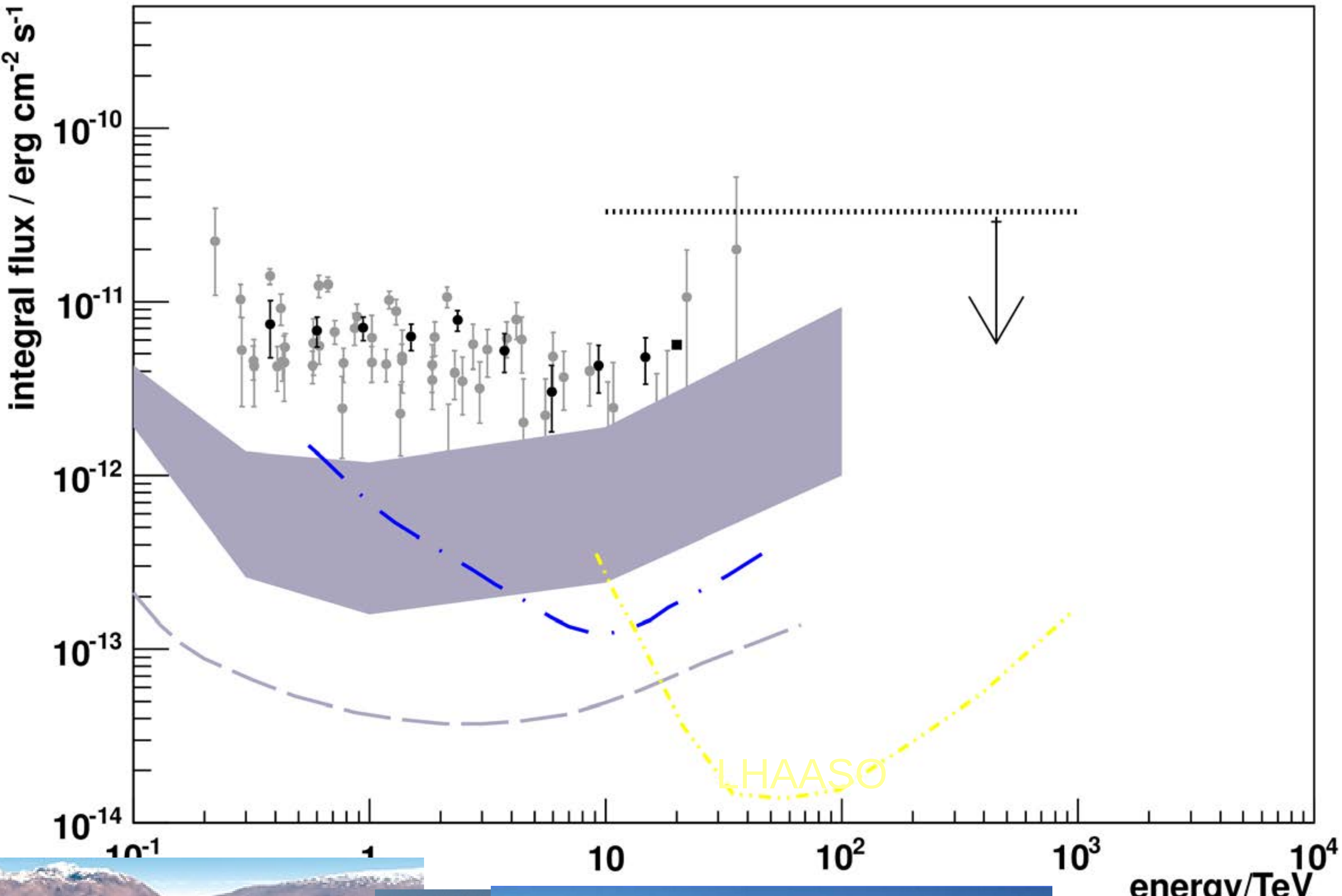
See wednesday: Sandoval

LHAASO



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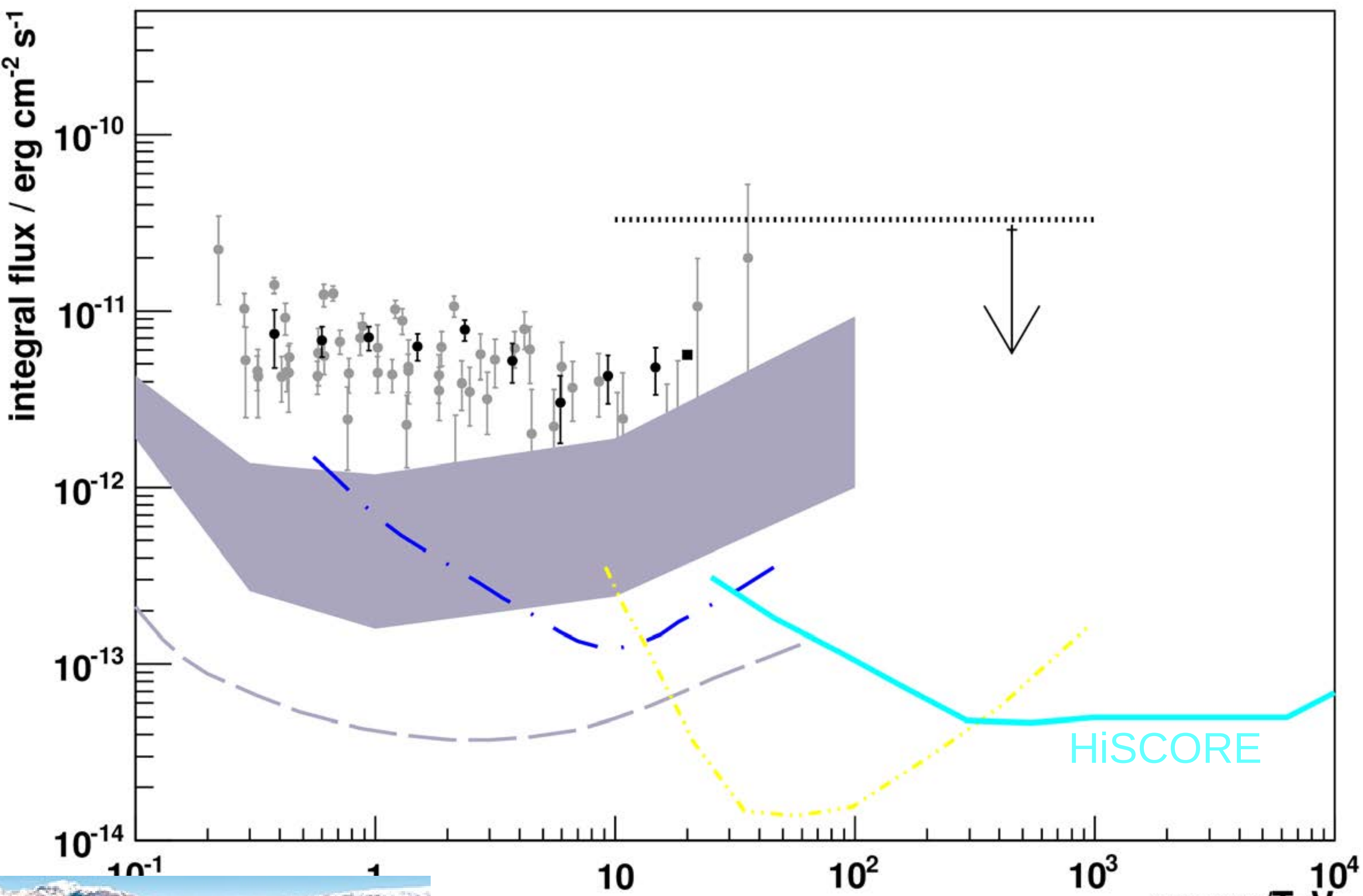
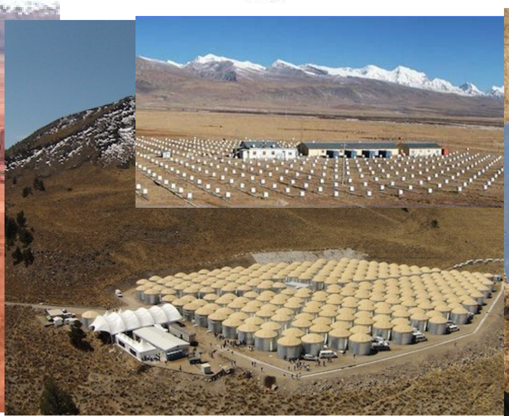
See Friday:
Simeone

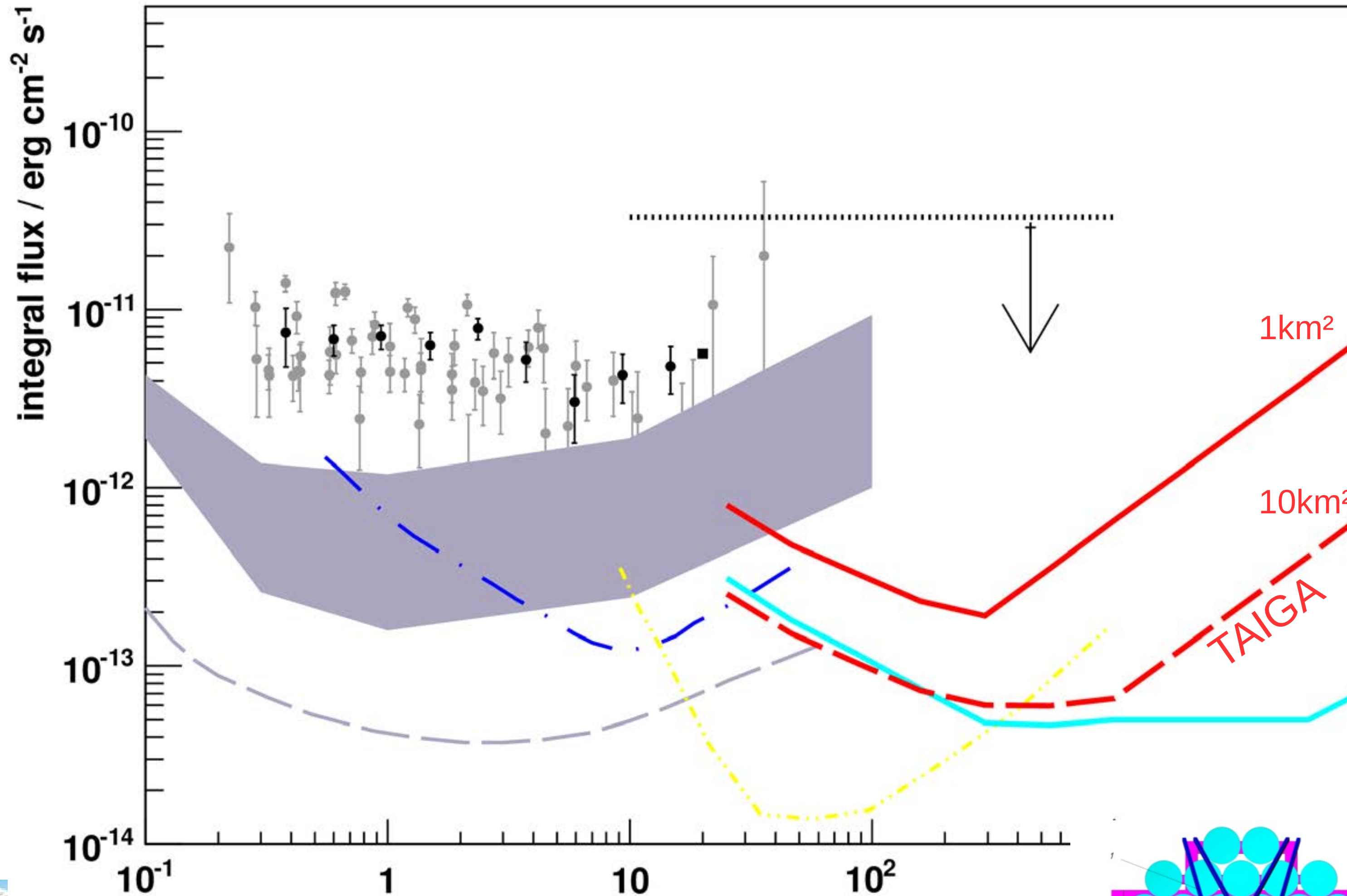
HiSCORE



integral flux / erg cm^{-2} s^{-1}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-1}
1
10
10^2
10^3
10^4
HiSCORE



TAIGA


integral flux / erg cm^{-2} s^{-1}
10^{-10}
10^{-11}
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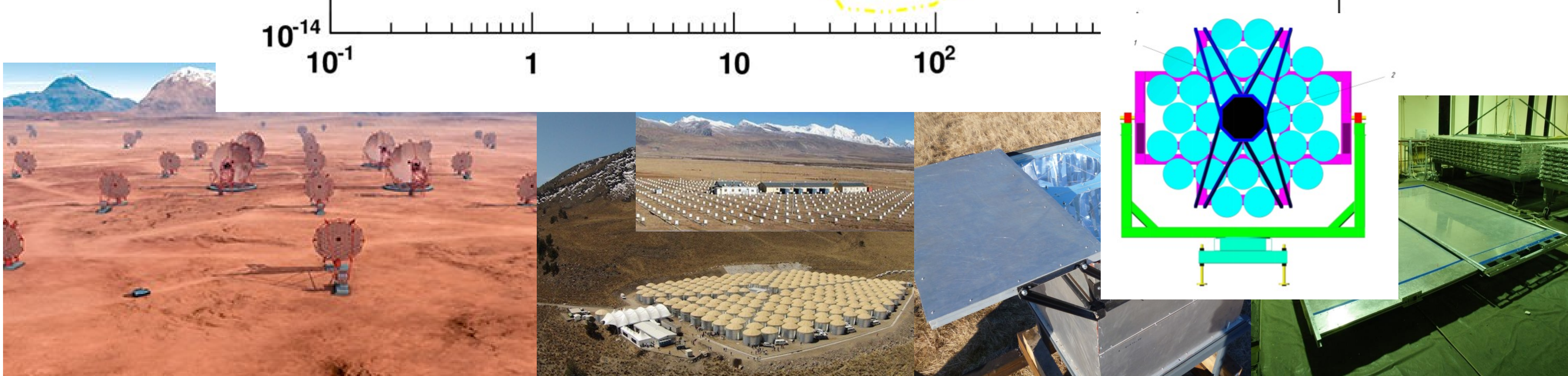
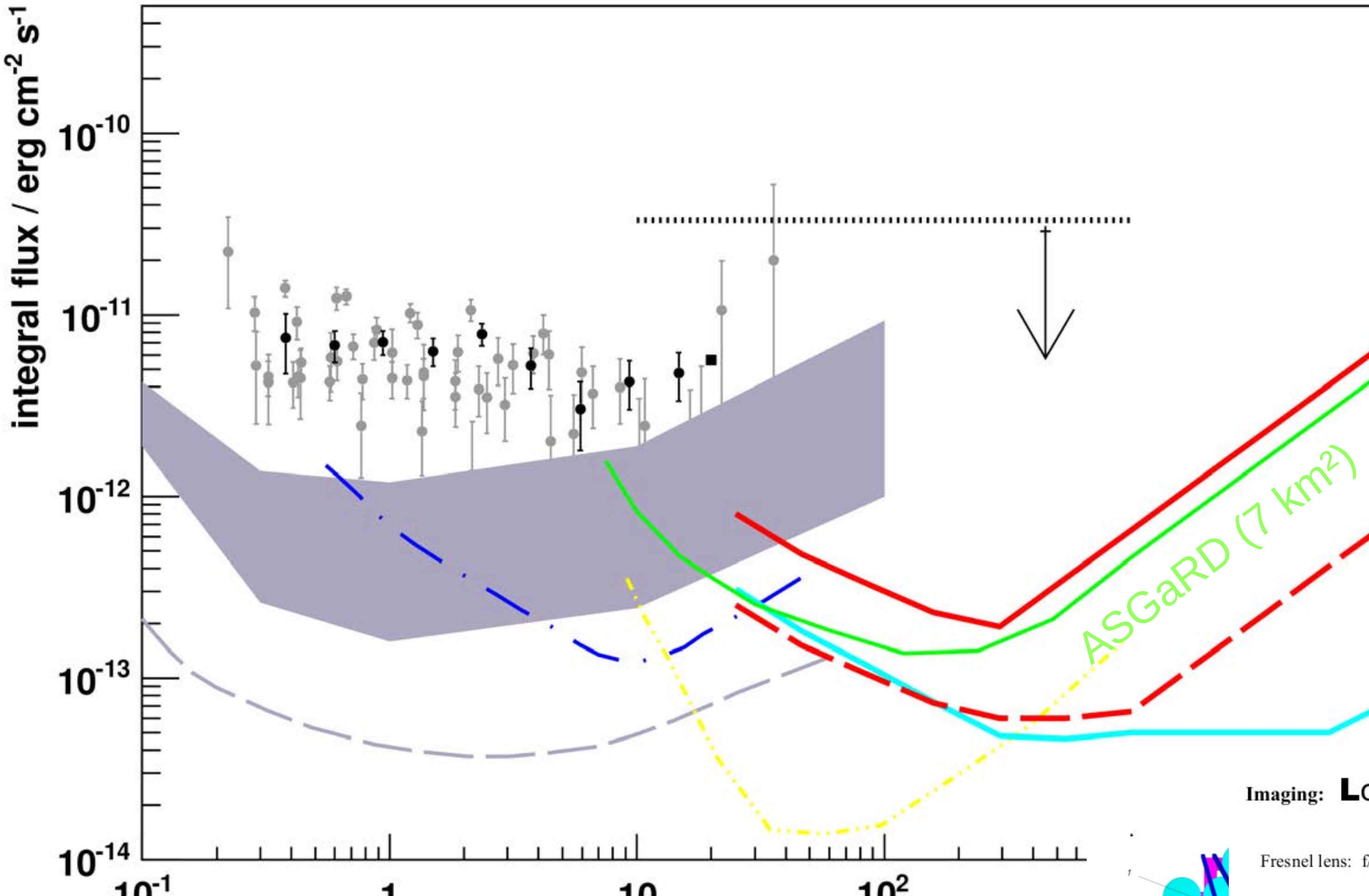
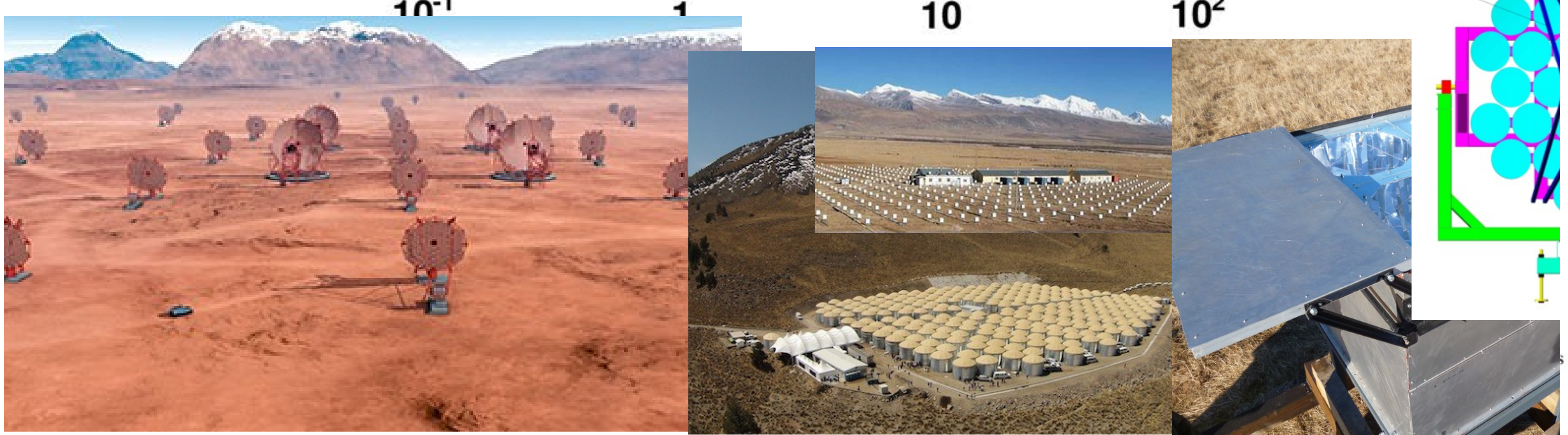
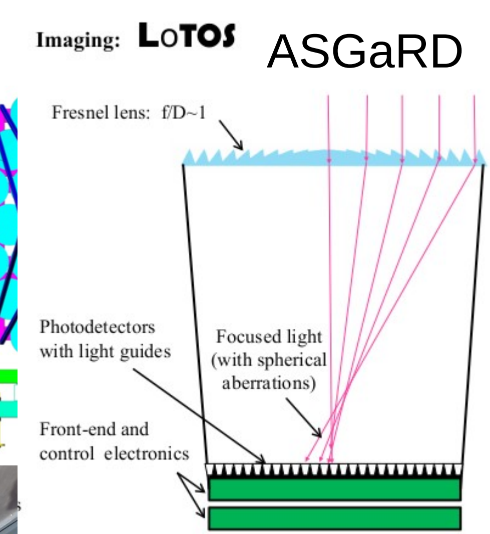
10^{-13}
10^{-14}
10^{-1}
1
10
10^{2}
1km²
10km²
TAIGA



ASGaRD


integral flux / erg cm-2 s-1
10-10
10-11
10-12
10-13
10-14
10-1
1
10
102
ASGaRD (7 km²)




Imaging: LOTOS
ASGaRD
Fresnel lens: f/D~1
Photodetectors
with light guides
Focused light
(with spherical
aberrations)
Front-end and
control electronics

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%

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From HiSCORE to TAIGA

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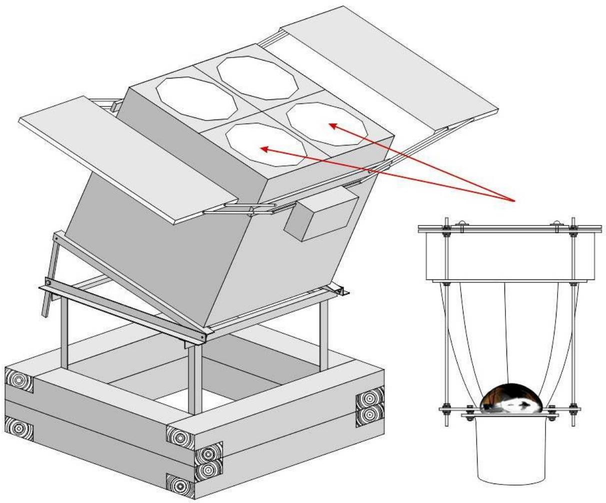
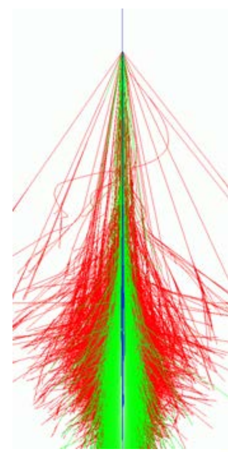
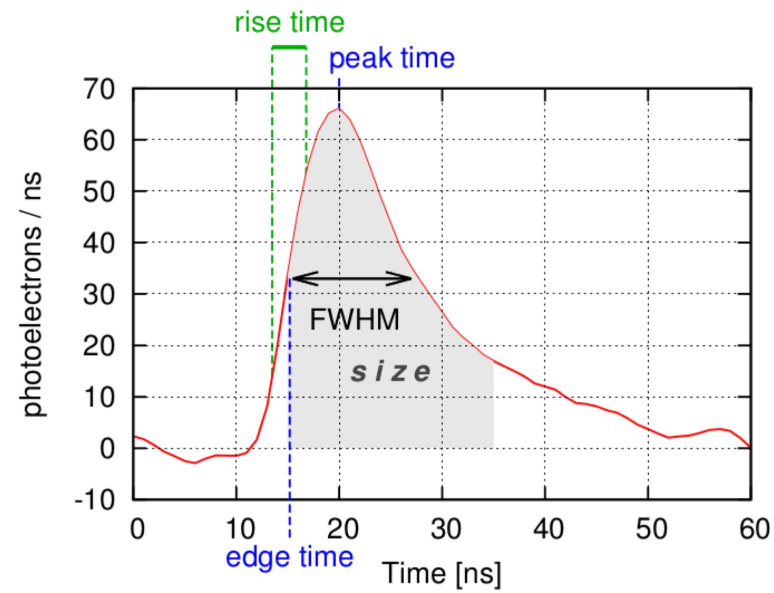
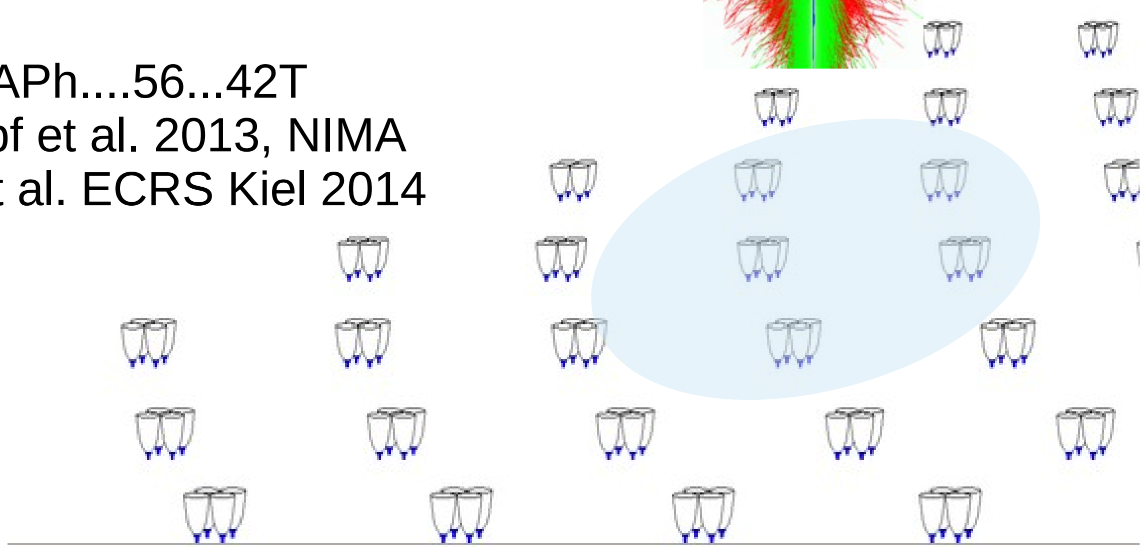
The HiSCORE Concept

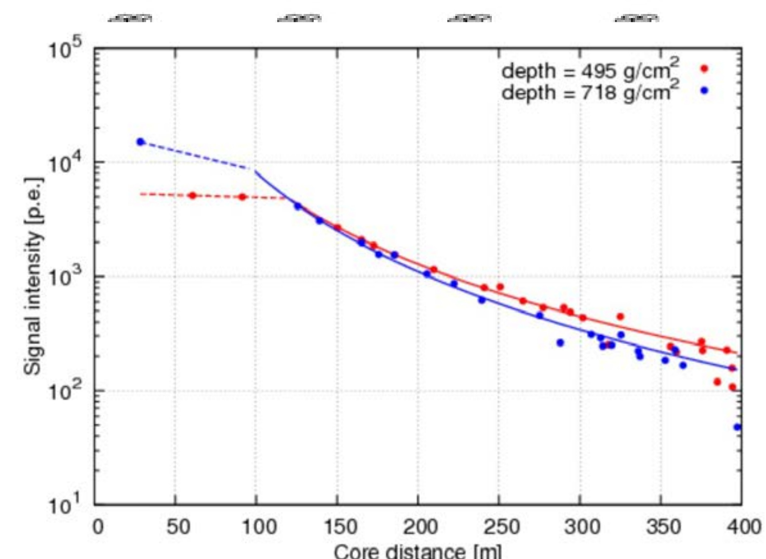






2014APh....56...42T
Hampf et al. 2013, NIMA
MT et al. ECRS Kiel 2014





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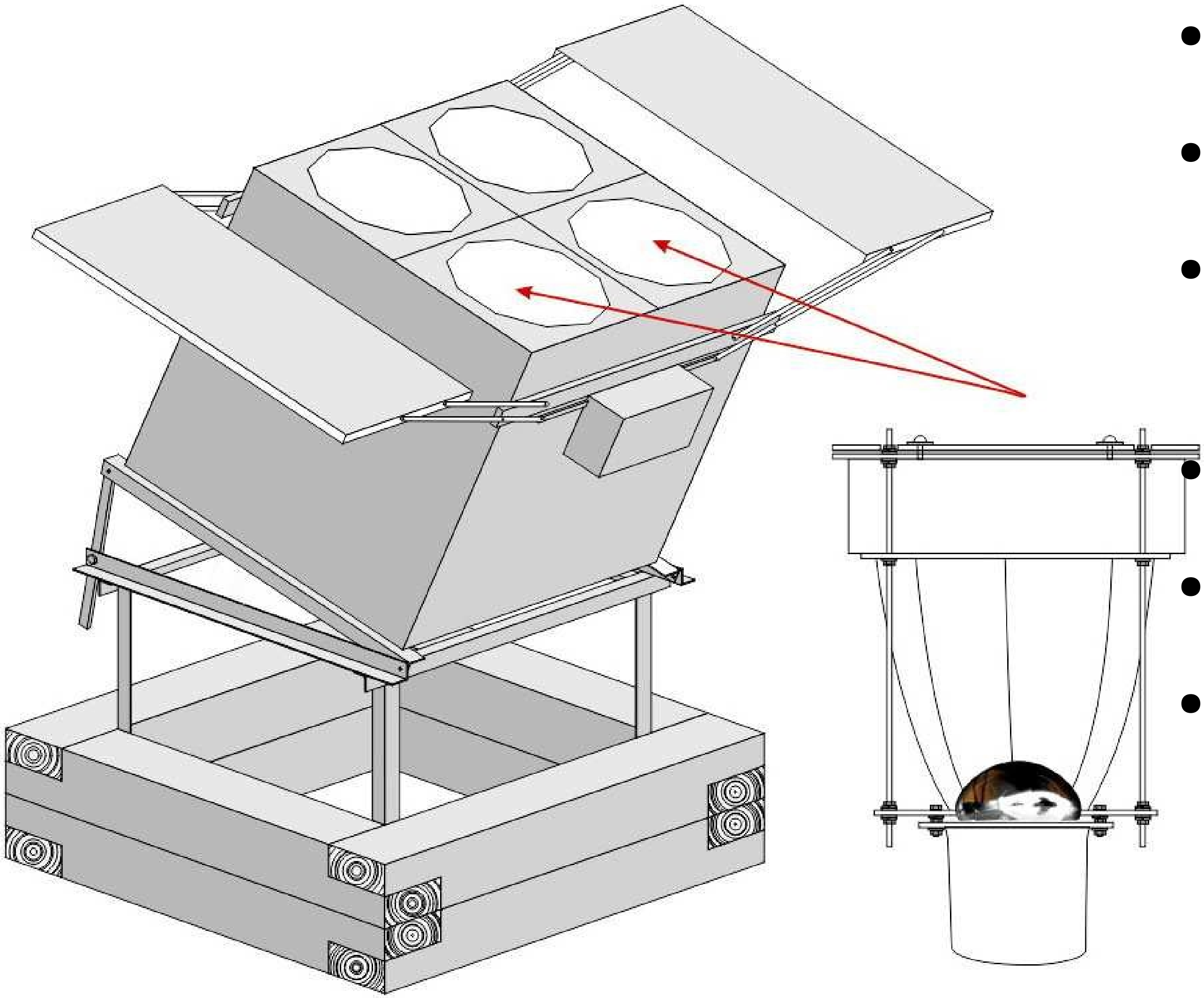
The HiSCORE Concept



- 4x 8inch PMTs
- Winston cones
- Lightcollection 0.5 m^2
- GHz readout
- 60° FoV
- “Tilting” for extension of sky coverage

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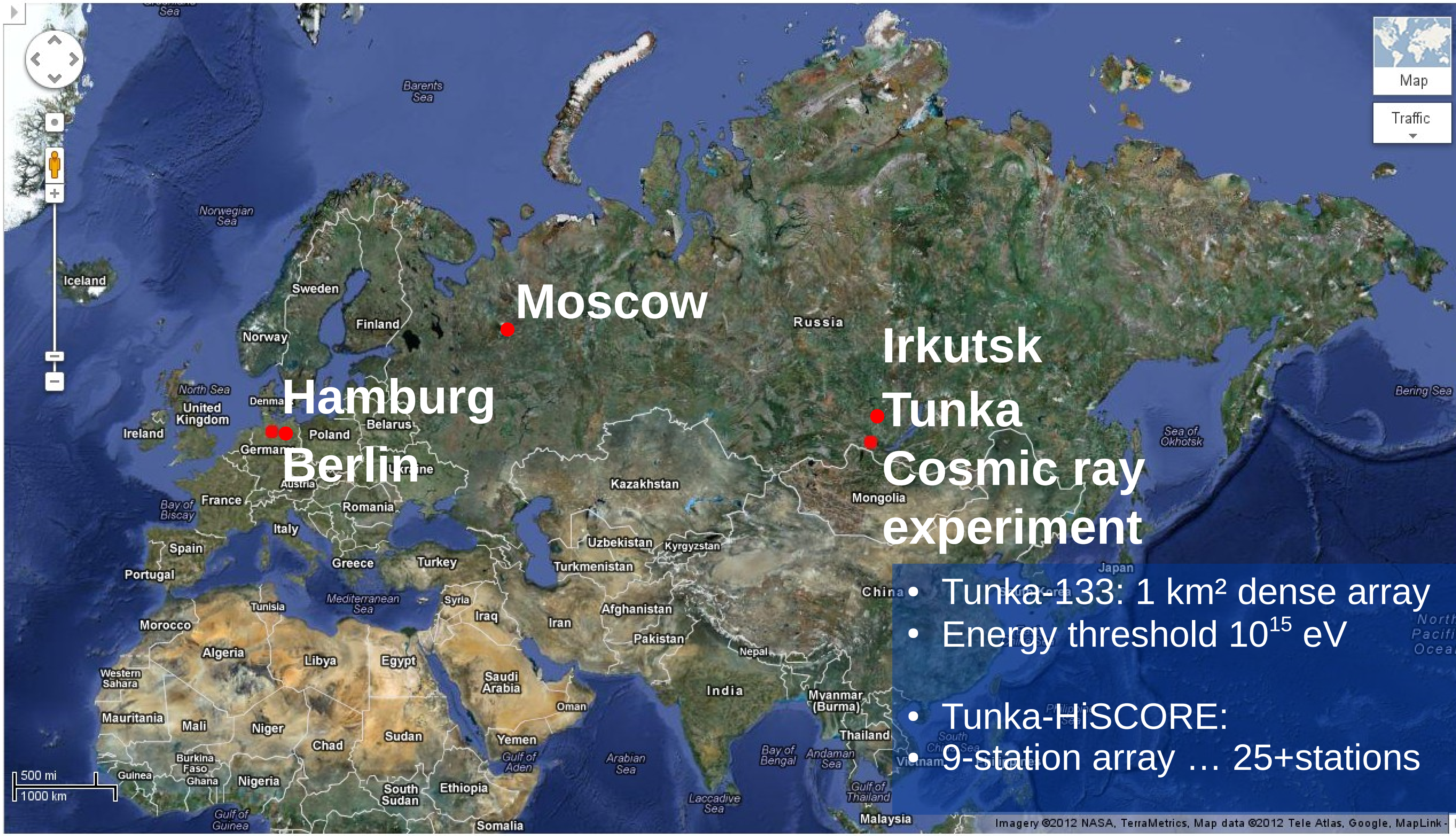
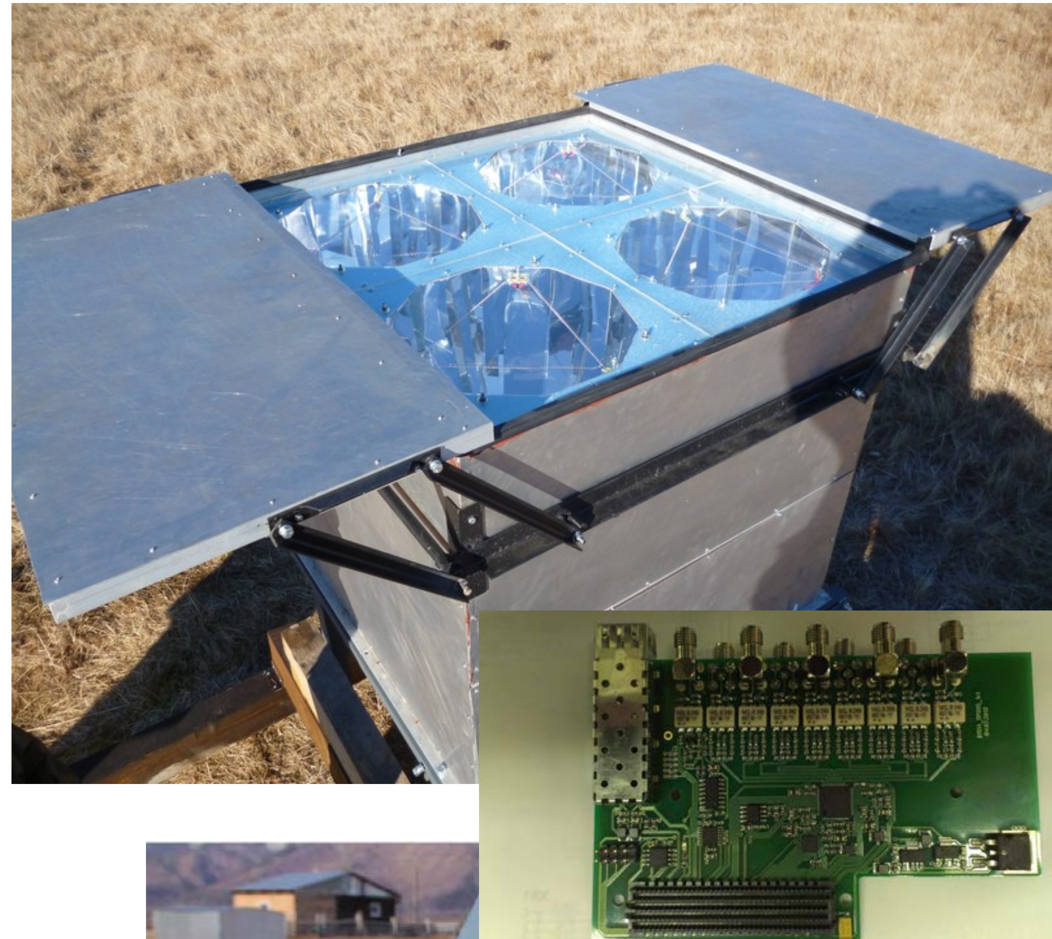
Tunka-HiSCORE



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

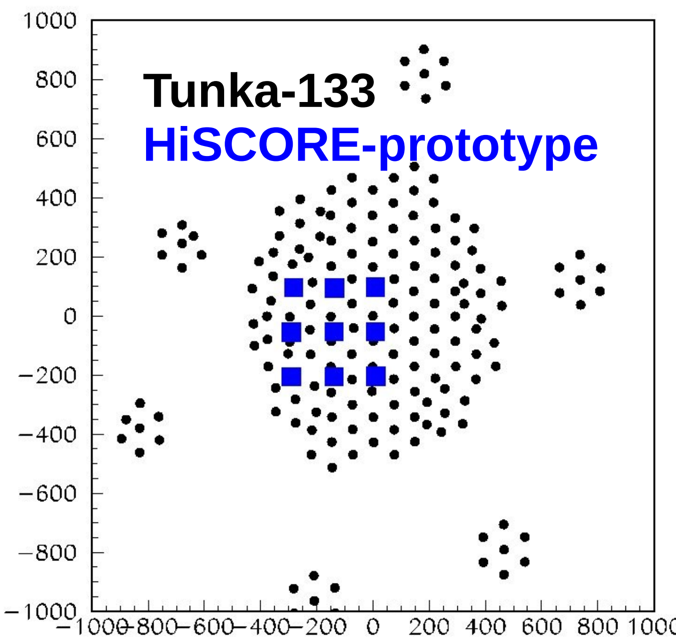
- Tunka-HiSCORE:
- 9-station array … 25+stations

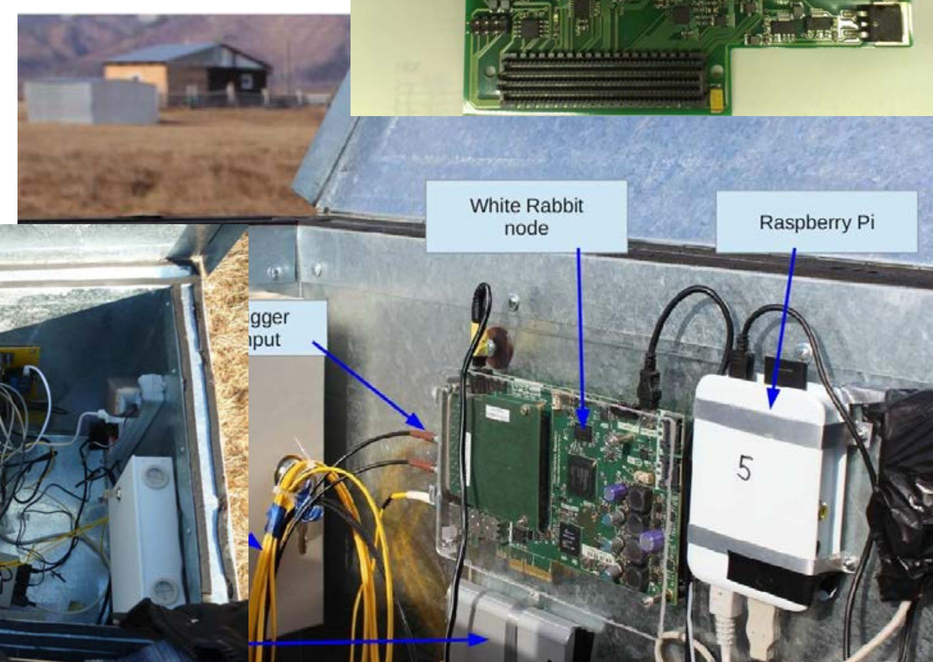
Tunka-HiSCORE



Prototype-array (2014):

- 9 stations, 300m X 300m
- 2 parallel DAQ systems
- Energy threshold: <30 TeV
- 0.5 m² light collection
- 4 channels (PMT + Cone)





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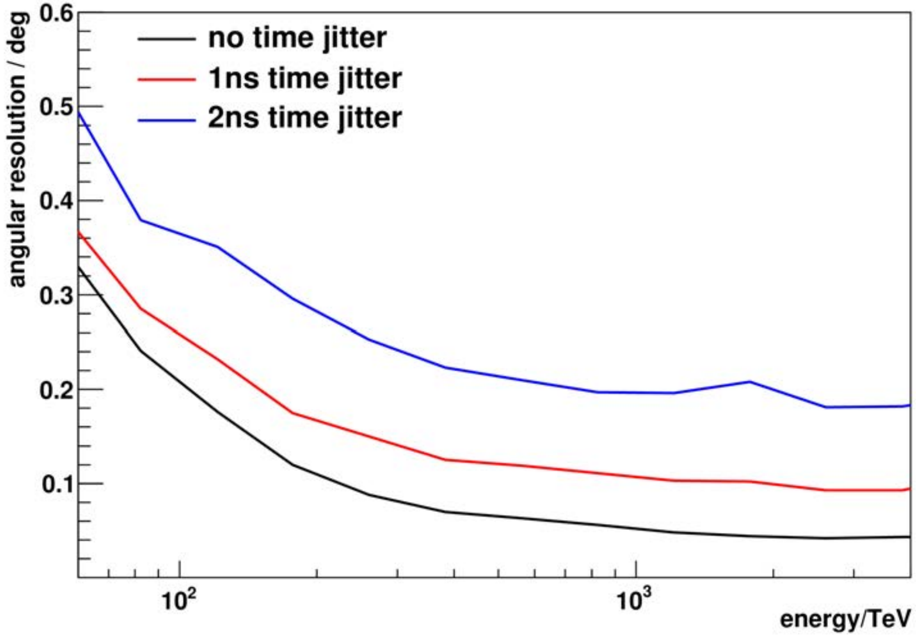
Angular resolution



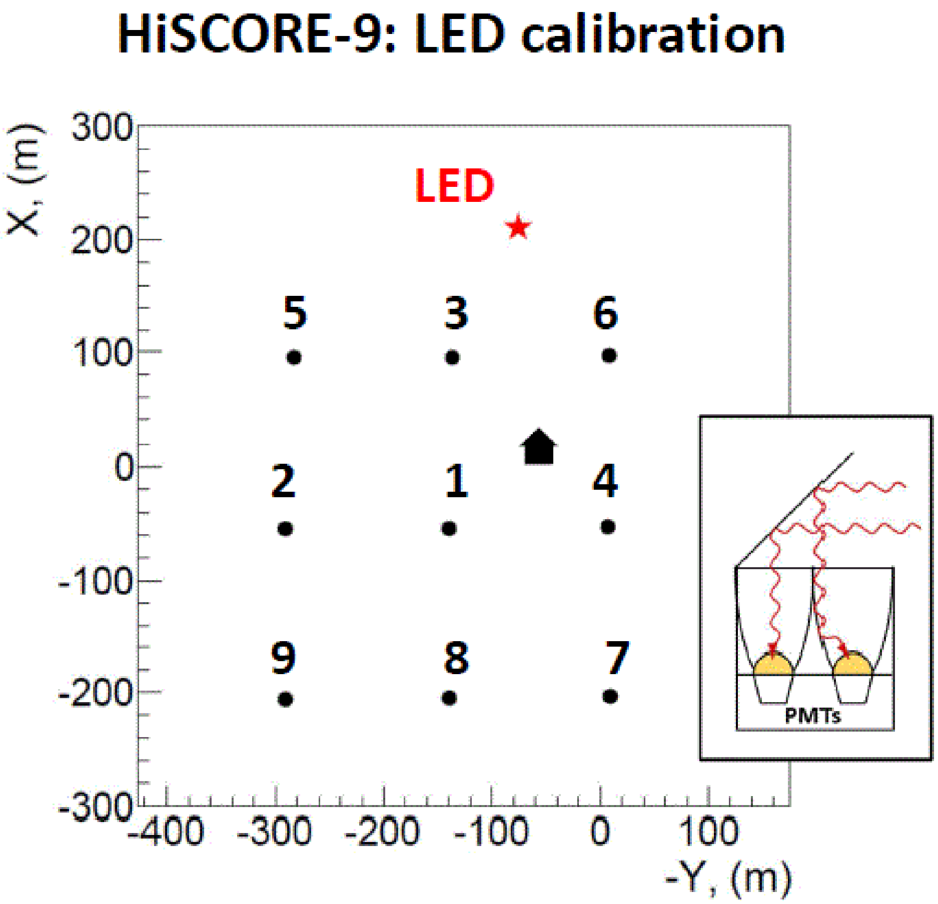
Crucial: relative time-synchronization <1ns

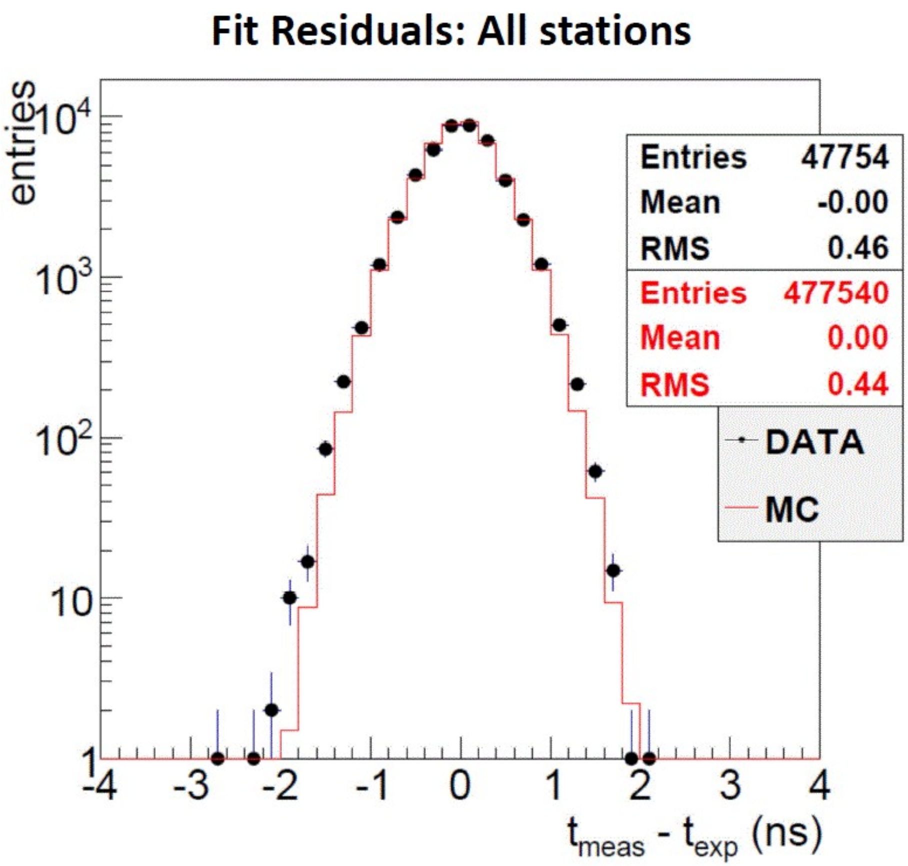
Two time-calibration systems:

DRS4 channel used for clock sampling (sent over fiber)

WhiteRabbit system (ethernet-based t-cal)

Time calibration





T-cal systems yield comparable accuraccies (<0.5 ns)

White Rabbit in laboratory: <60 ps resolution achievable (PoS ICRC 2015, Wischnewski et al.)

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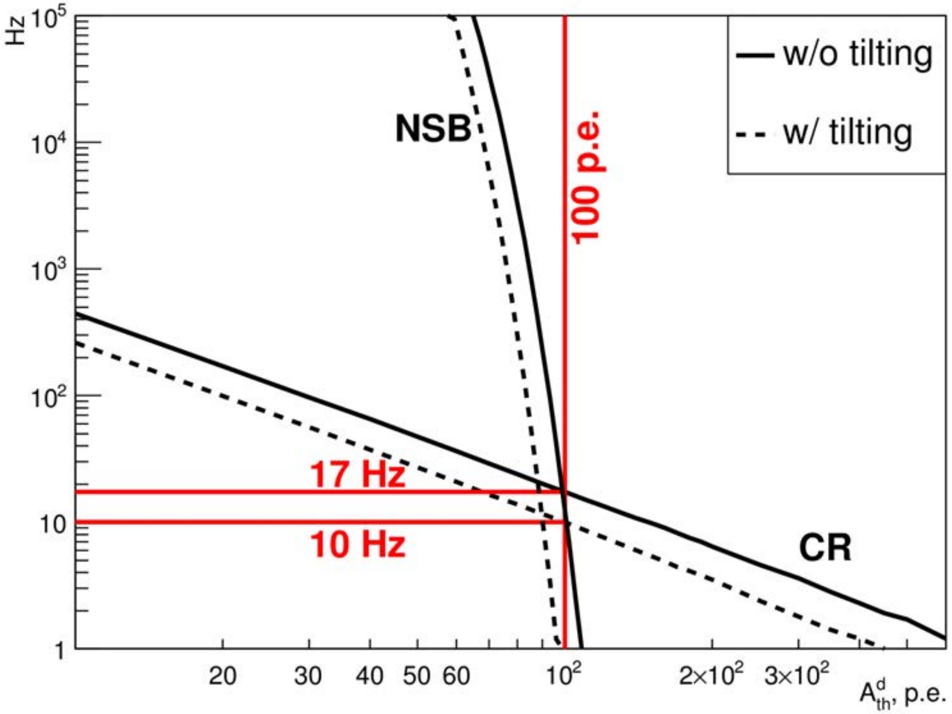
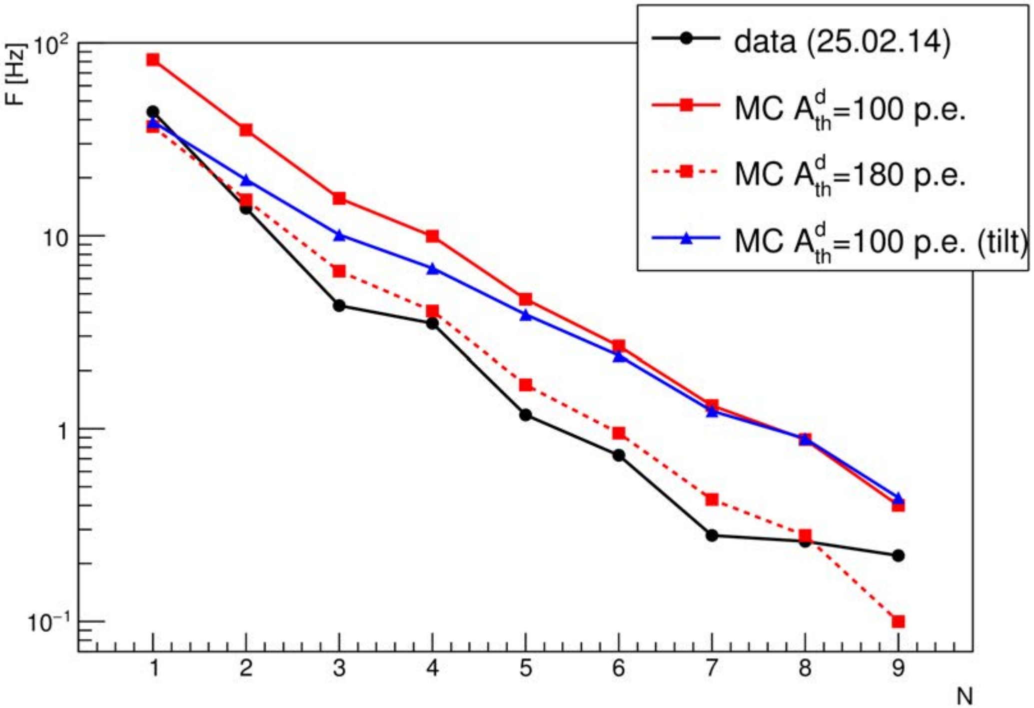
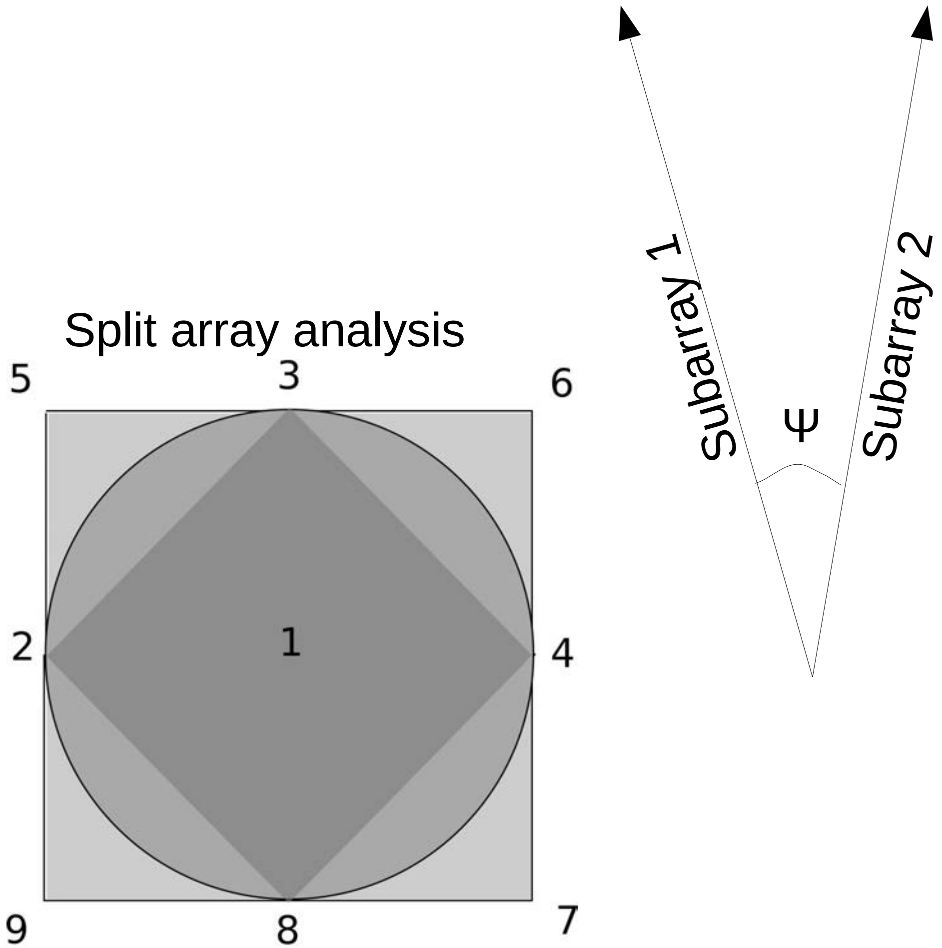
Tunka-HiSCORE data vs MC



S. Epimakhov, PoS, ICRC 2015



Tunka-HiSCORE real data



Reconstruct using two different subarrays

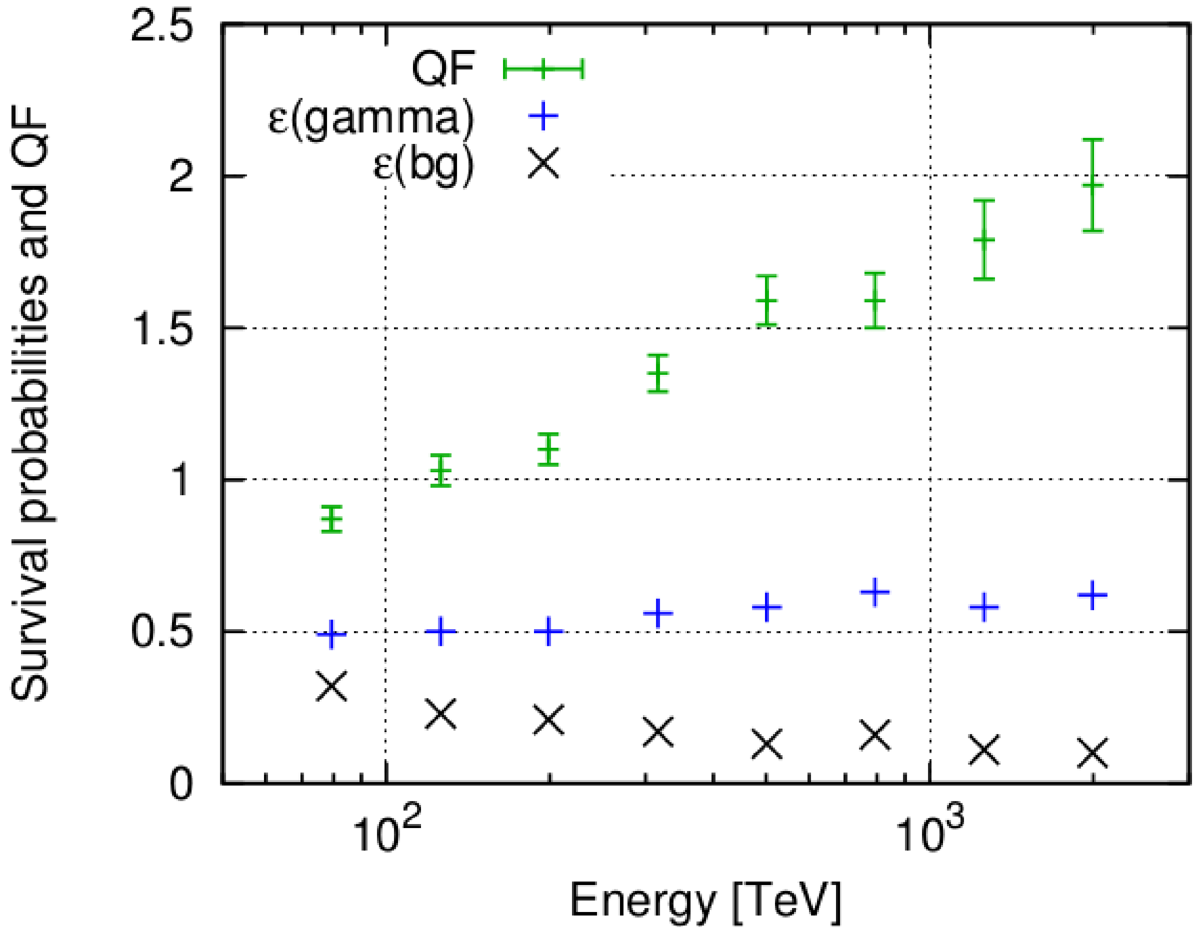
Tested for 9-station array

Resulting resolutions (hadrons):

- Direction: 0.19°
- Core position: 4m
- Energy: 10%

PoS, ICRC 2015, Porelli et al. And Epimakhov et al.

Particle separation Q-factor (only timing array)



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

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Tunka-HiSCORE → TAIGA

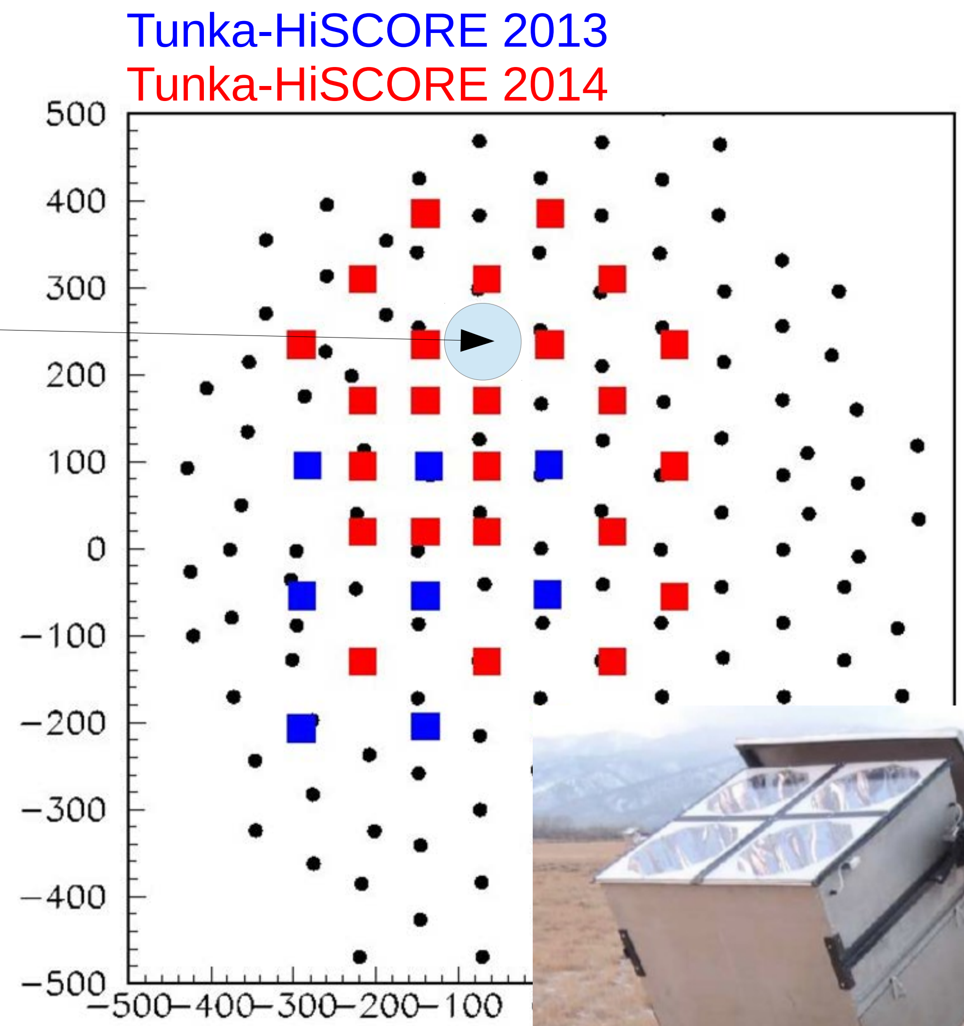
Tunka Advanced Instrument for Gamma ray and cosmic ray physics

10/2014: extension

- Total: 29 stations
- Tilting mode
- 0.25 km²

2015+:

- First telescope
- Hybrid timing+imaging
- In total 10 telescopes planned
- Muon detectors



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TAIGA collaboration

[1]Institute of Applied Physics, Irkutsk State University, Irkutsk, Russia
[2]Institute for Computer Science, Humboldt-University Berlin, Rudower Chaussee 25, 12489 Berlin, Germany
[3]DESY, Platanenallee 6, 15738 Zeuthen, Germany
[4]National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russia
[5]Institut für Experimentalphysik, Luruper Chaussee 149, 22761 Hamburg, Germany
[6]Dipartimento di Fisica Generale Universiteta di Torino and INFN, Torino, Italy
[7]Werner Heisenberg Institut, Föhringer Ring 6, 80805, München, Germany
[8]IZMIRAN, Troitsk, Moscow Region, Russia
[9]Joint Institute for Nuclear Research, Joliot-Curie 6, 141980 Dubna, Moscow region, Russia
[10]Institute for Nuclear Research of the Russian Academy of Sciences 60th October Anniversary st., 7a, 117312, Moscow, Russia
[11]Skobeltsyn institute for Nuclear Physics, Lomonosov Moscow State University, 1 Leninskie gory, 119991 Moscow, Russia
[12]Institute of Space Science, Bucharest, Romania

HiSCORE array + IACTs + Muon detectors

Combining a timing array with an imaging telescope

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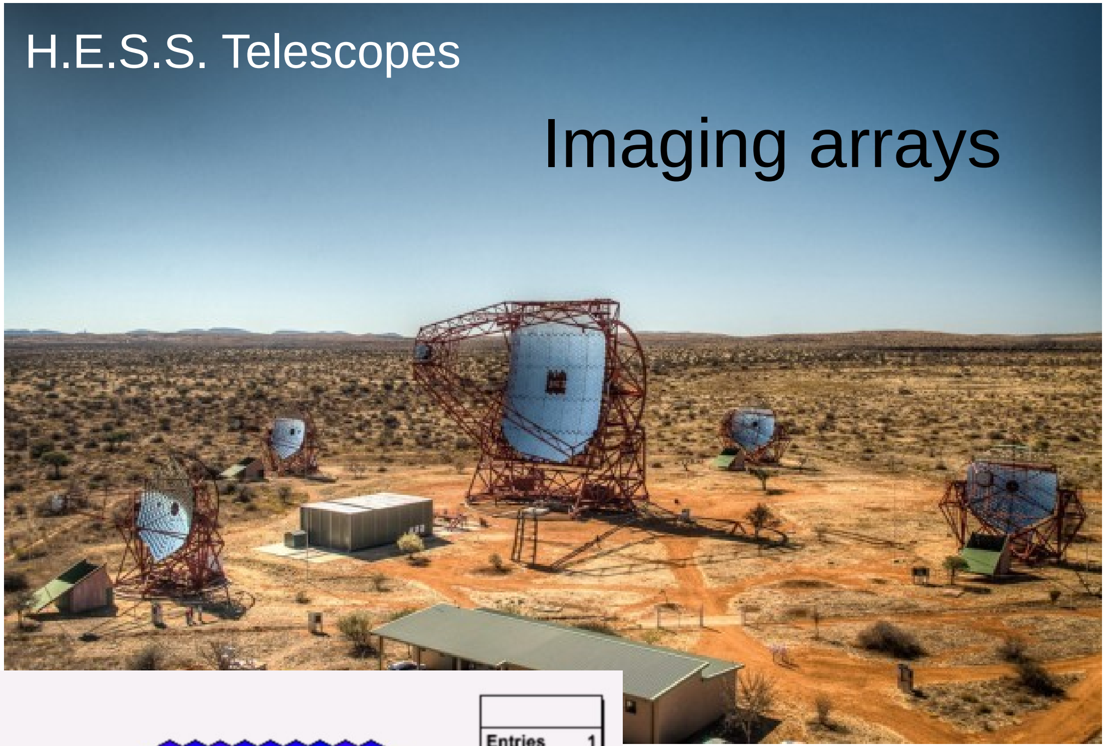
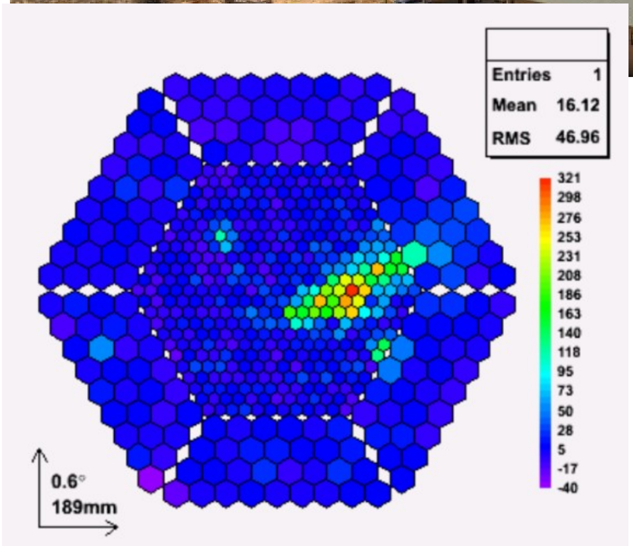
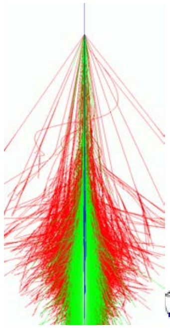
Air Cherenkov imaging and timing

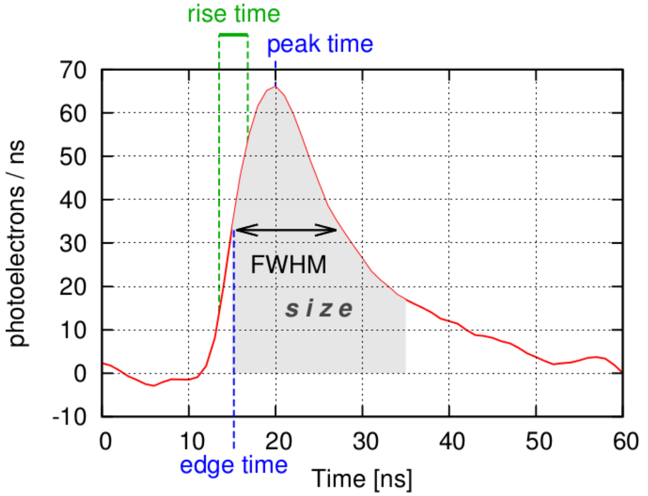


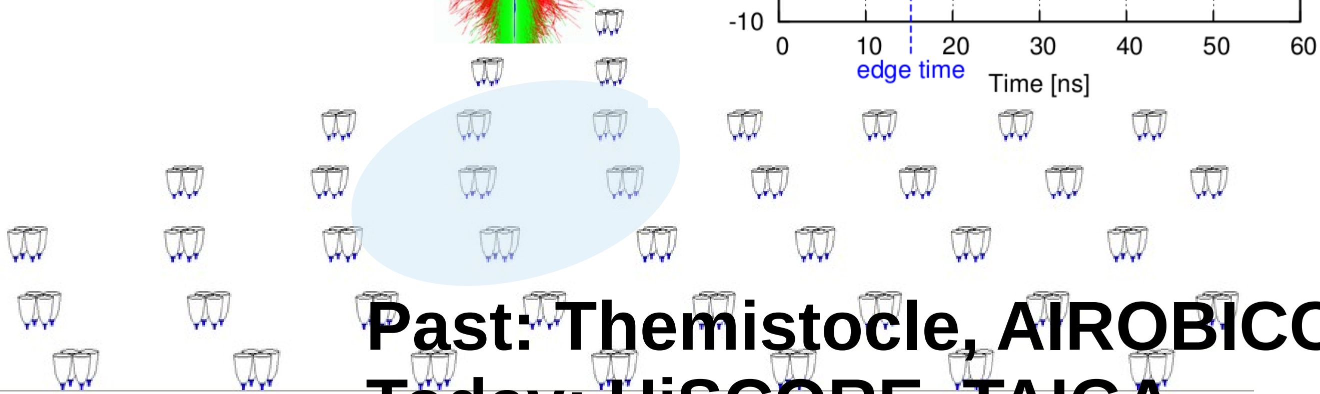


MAGIC camera image

Timing arrays
(=non-imaging)







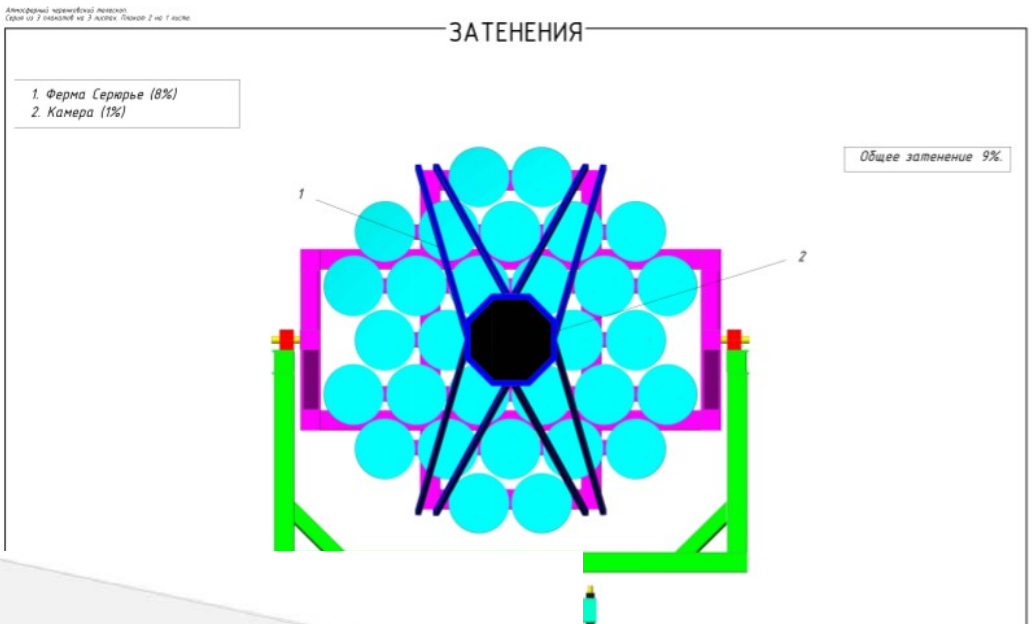
Past: Themistocle, AIROBICC
Today: HiSCORE, TAIGA

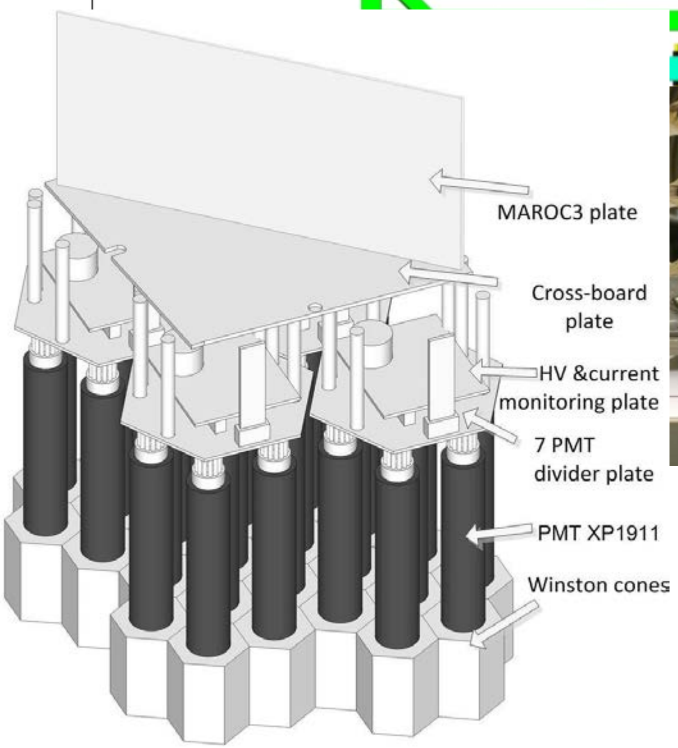
Air Cherenkov imaging and timing

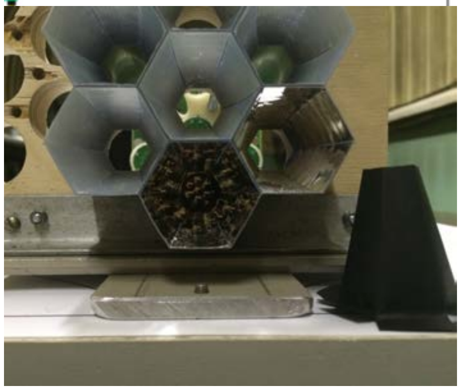
	Imaging ACTs	Timing arrays
Direction	Image orientation	Shower front arrival times
Particle type	Image shape	Lateral density function Arrival times Time width (FWHM)
Energy	Ch. photon count	Ch. photon count

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













SKF
05.12.2014 12:19


Timing and imaging hybrid detection

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Telescope image scaling

Central reconstruction parameter: Shower core position D_K

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

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

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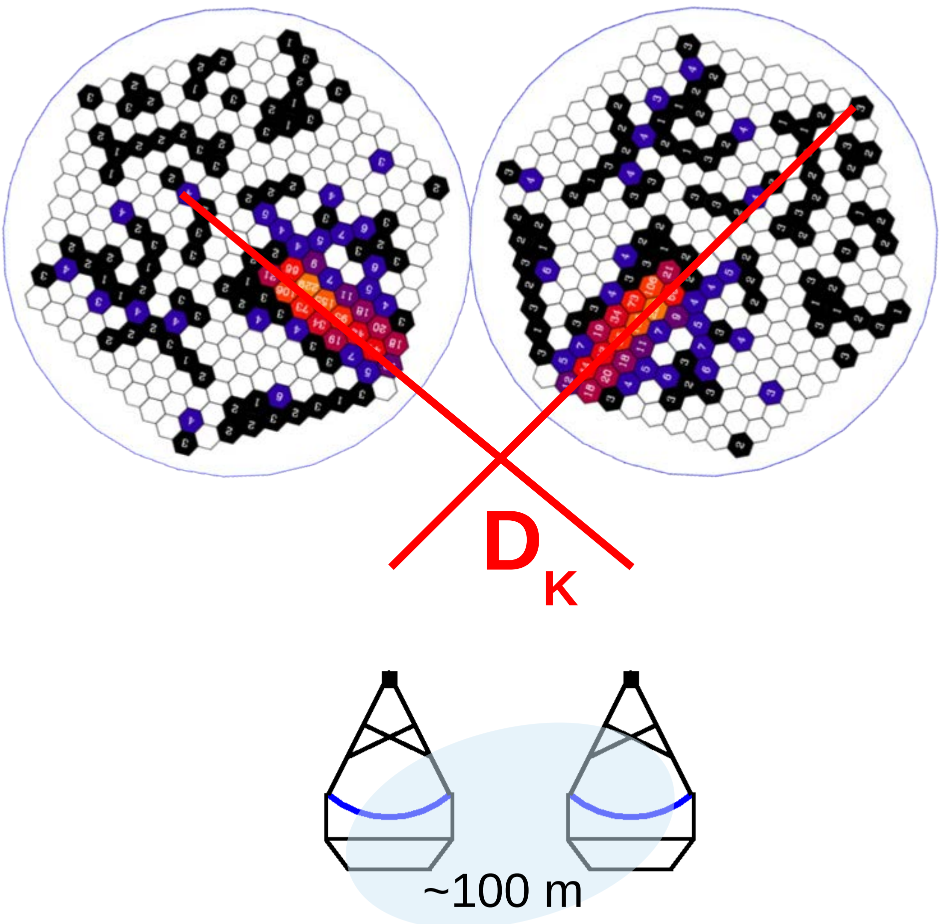
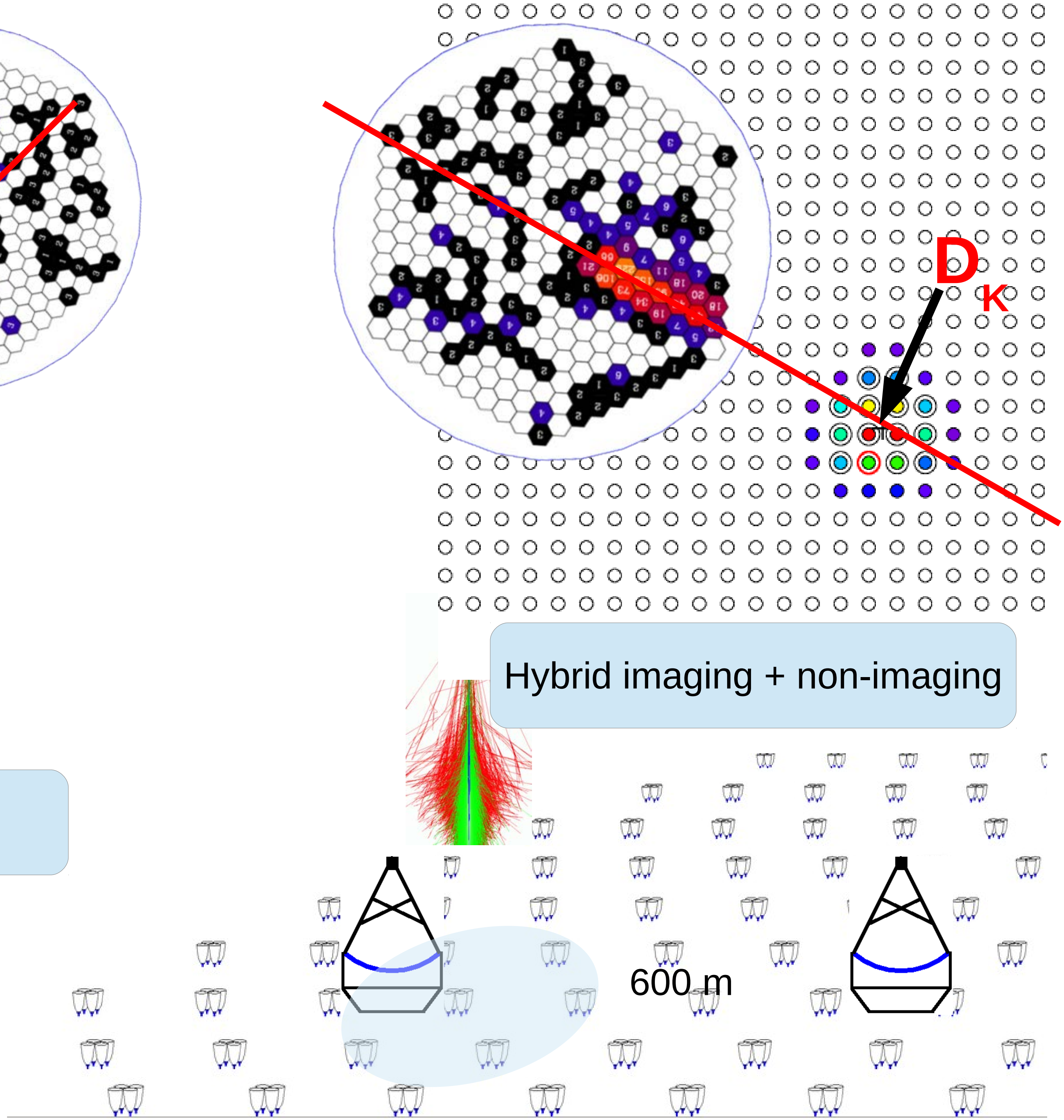
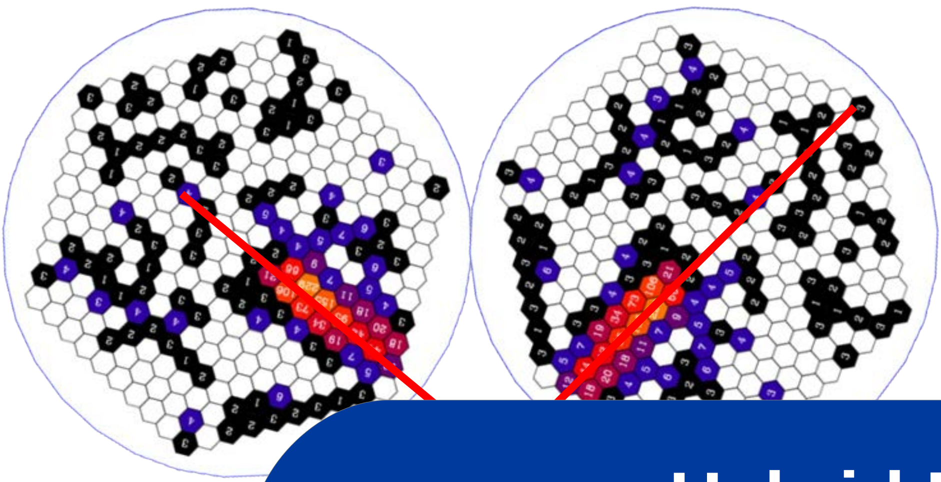
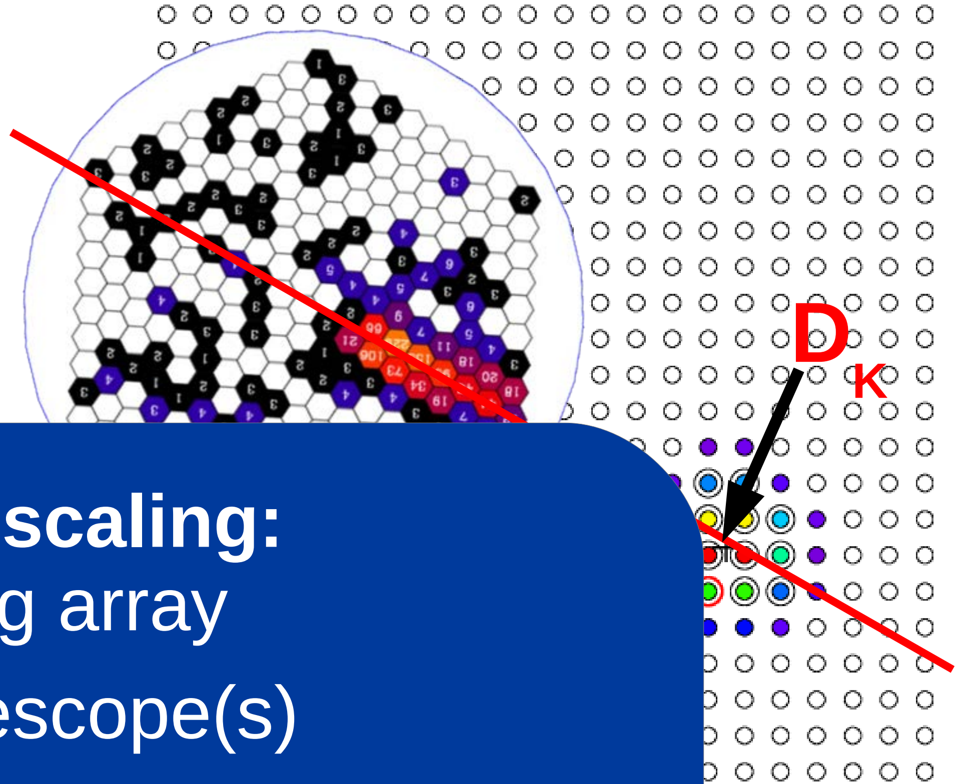


Imaging (stereo)



Hybrid imaging + non-imaging





Hybrid Image scaling:

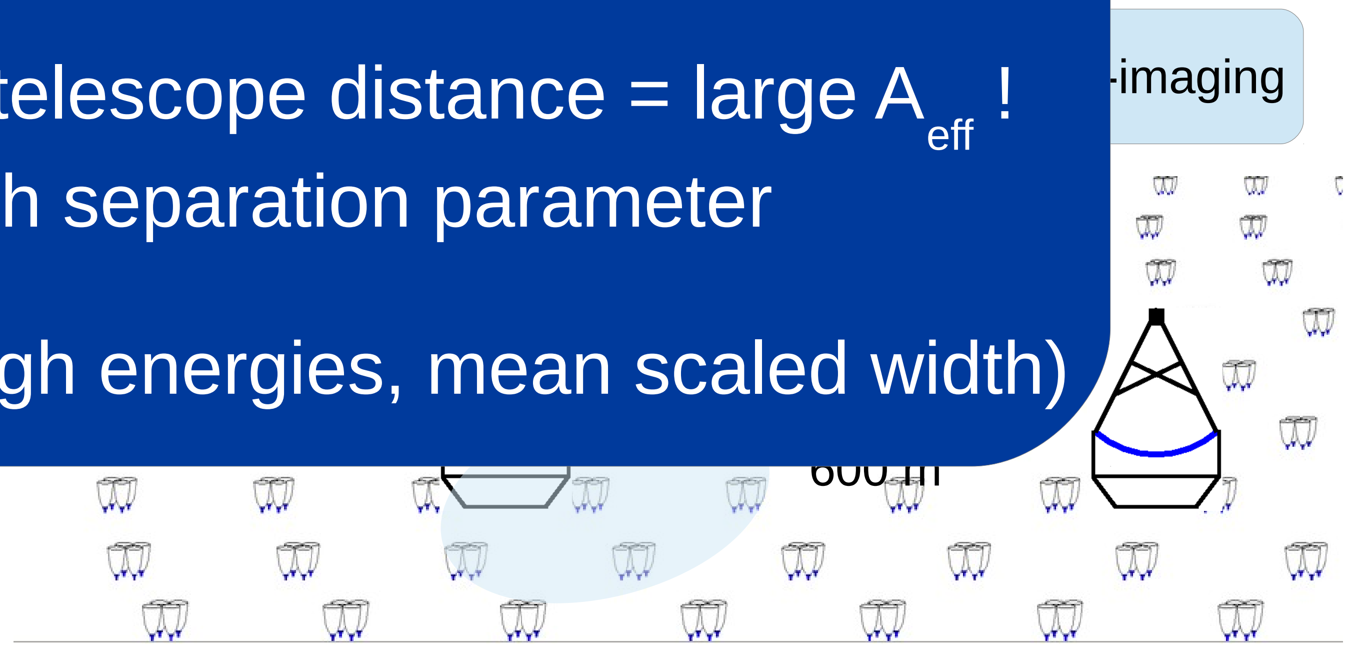
D_K from timing array

Image from telescope(s)

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

→ scaled width separation parameter

(+ stereo at high energies, mean scaled width)



HiSCORE + IACTs

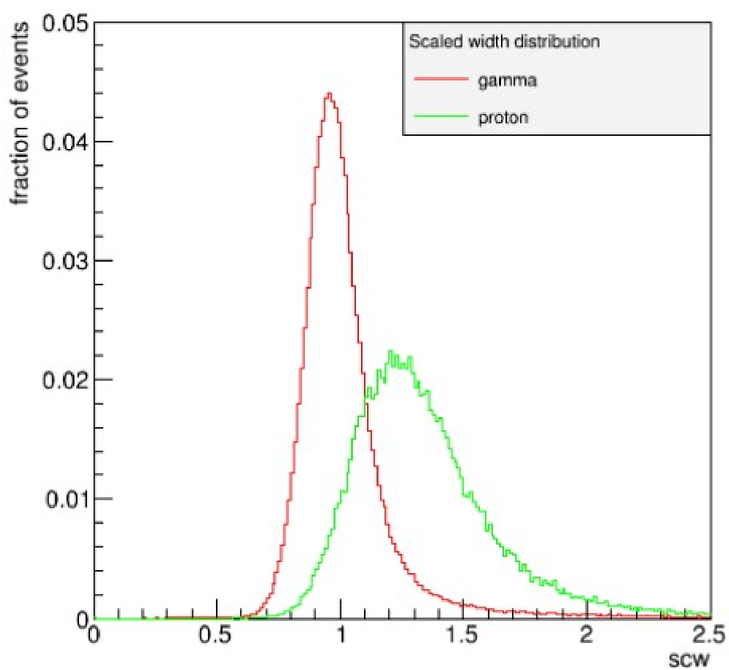
Preliminary results hybrid width scaling:

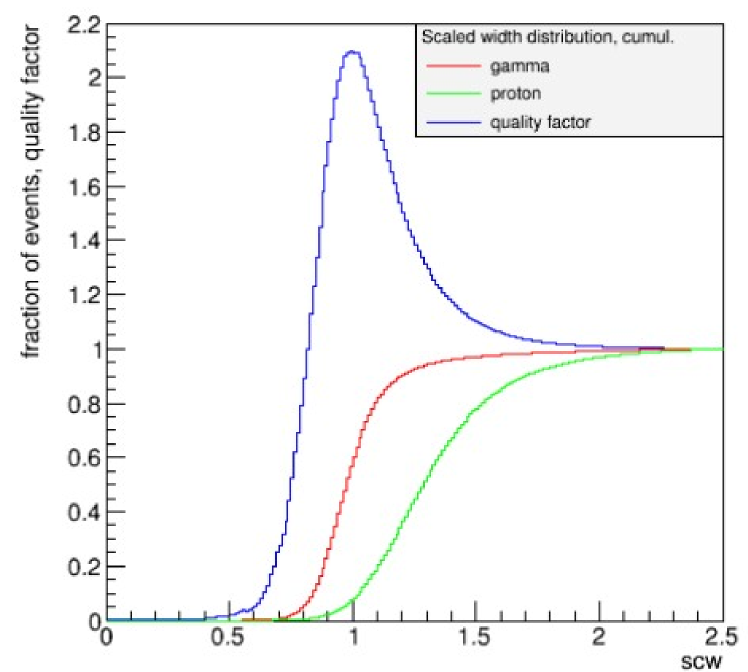
- Separation quality significantly improved
- Increases total area as compared to stereoscopic array

Also see:
Kunnas et al. 2015,
PoS ICRC 2015

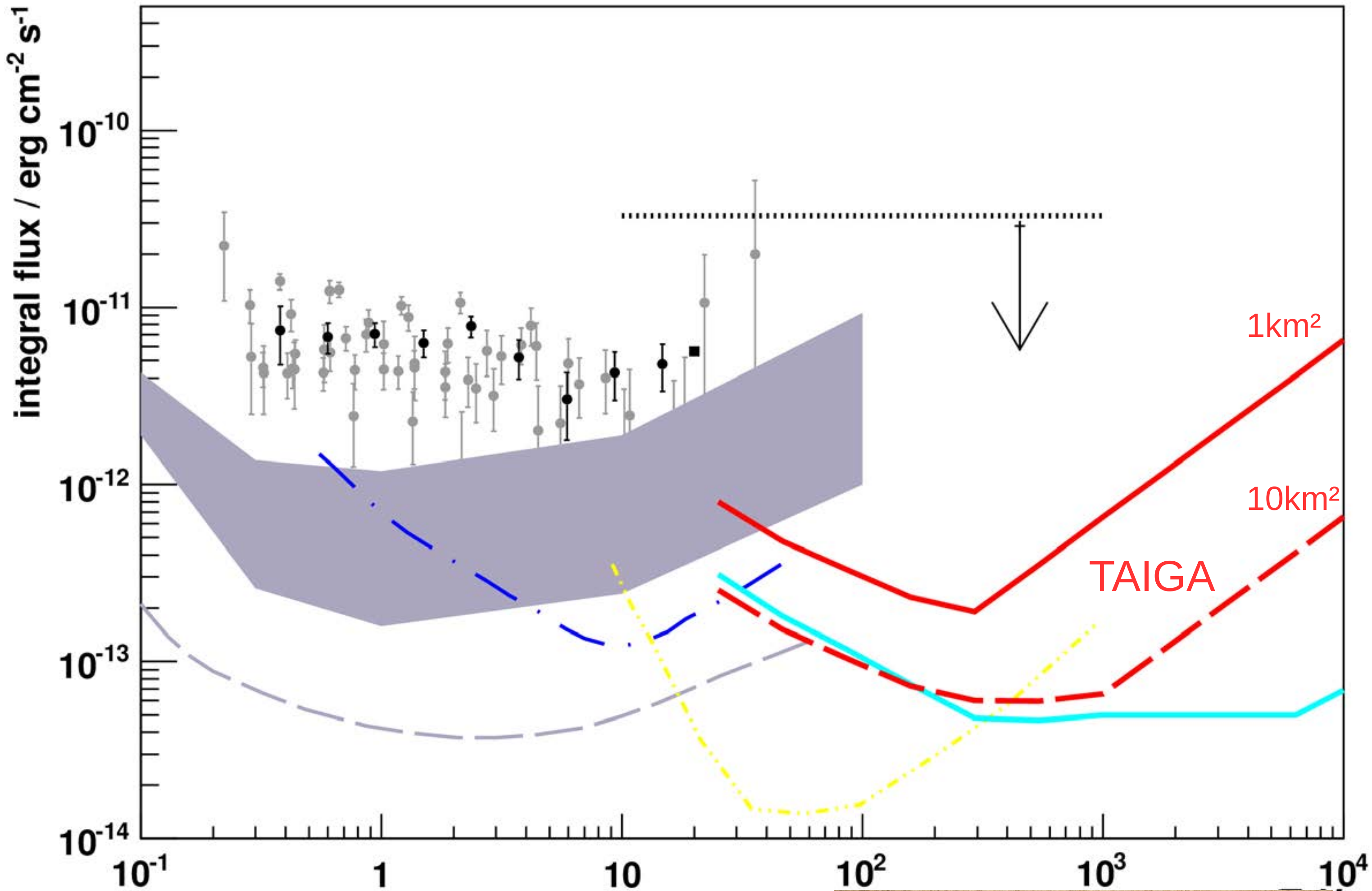
Apply scaled width cut:

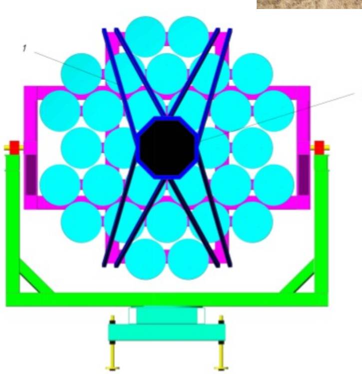
Q-factor ~2

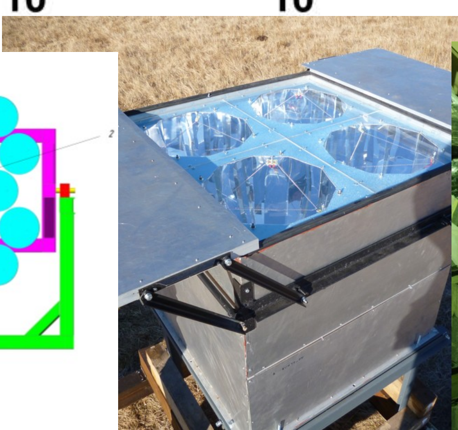


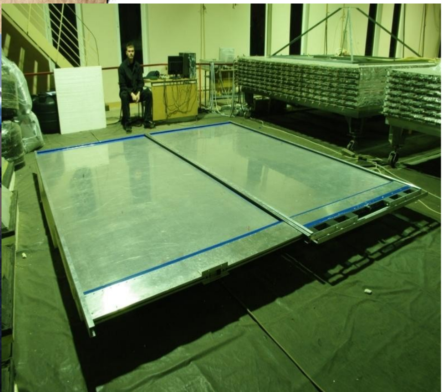


TAIGA


integral flux / erg cm^{-2} s^{-1}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
1km²
10km²
TAIGA

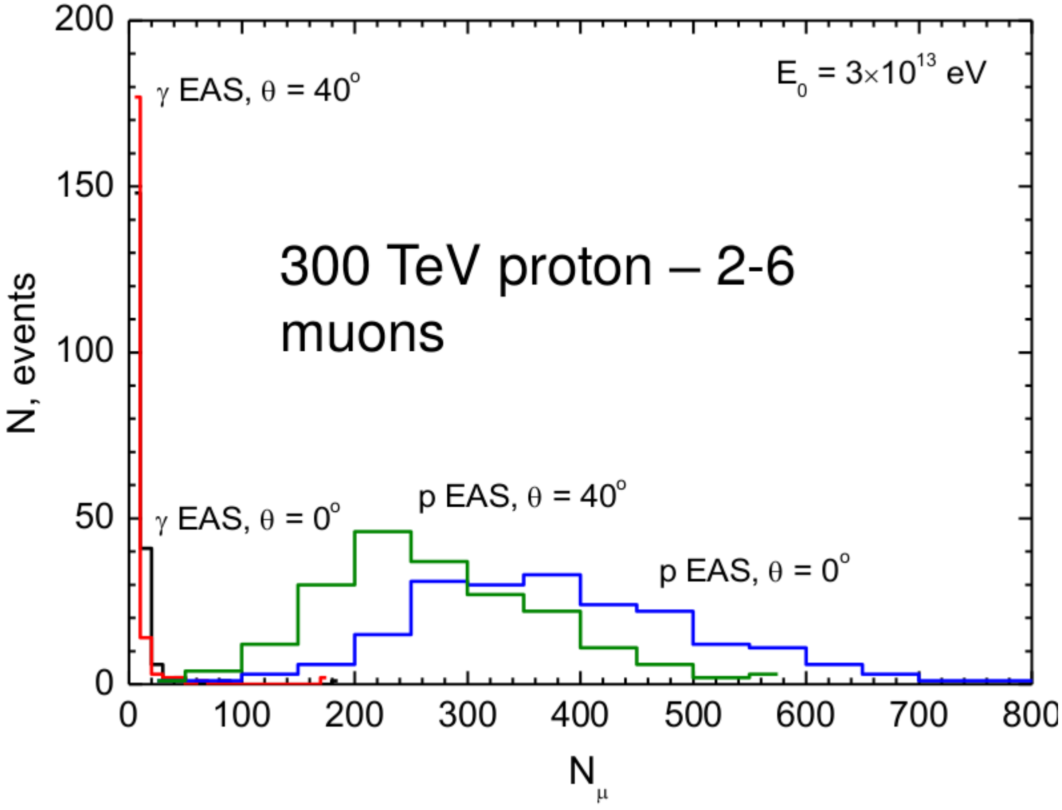


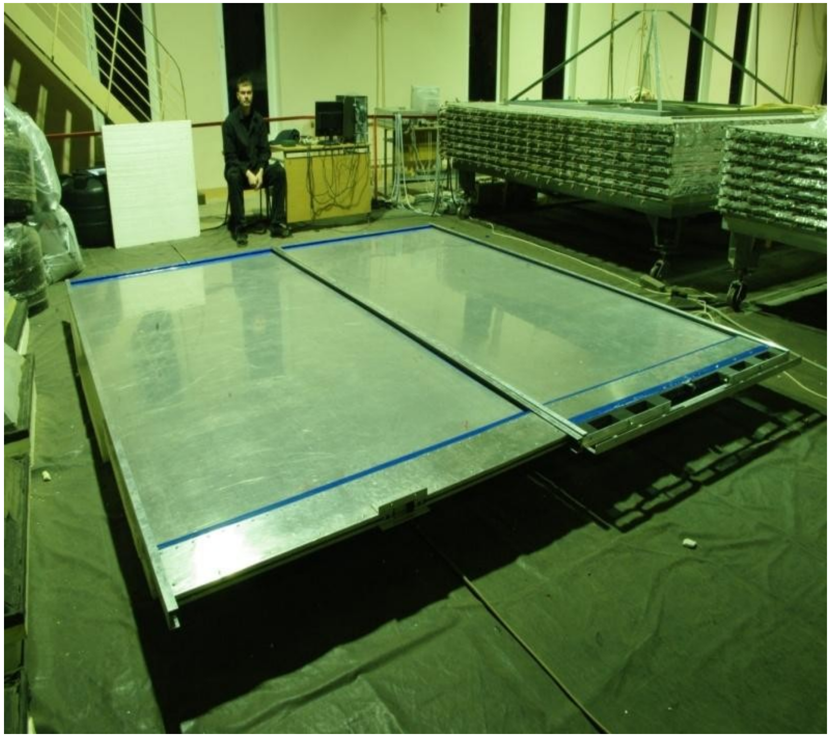




TAIGA Muon detectors

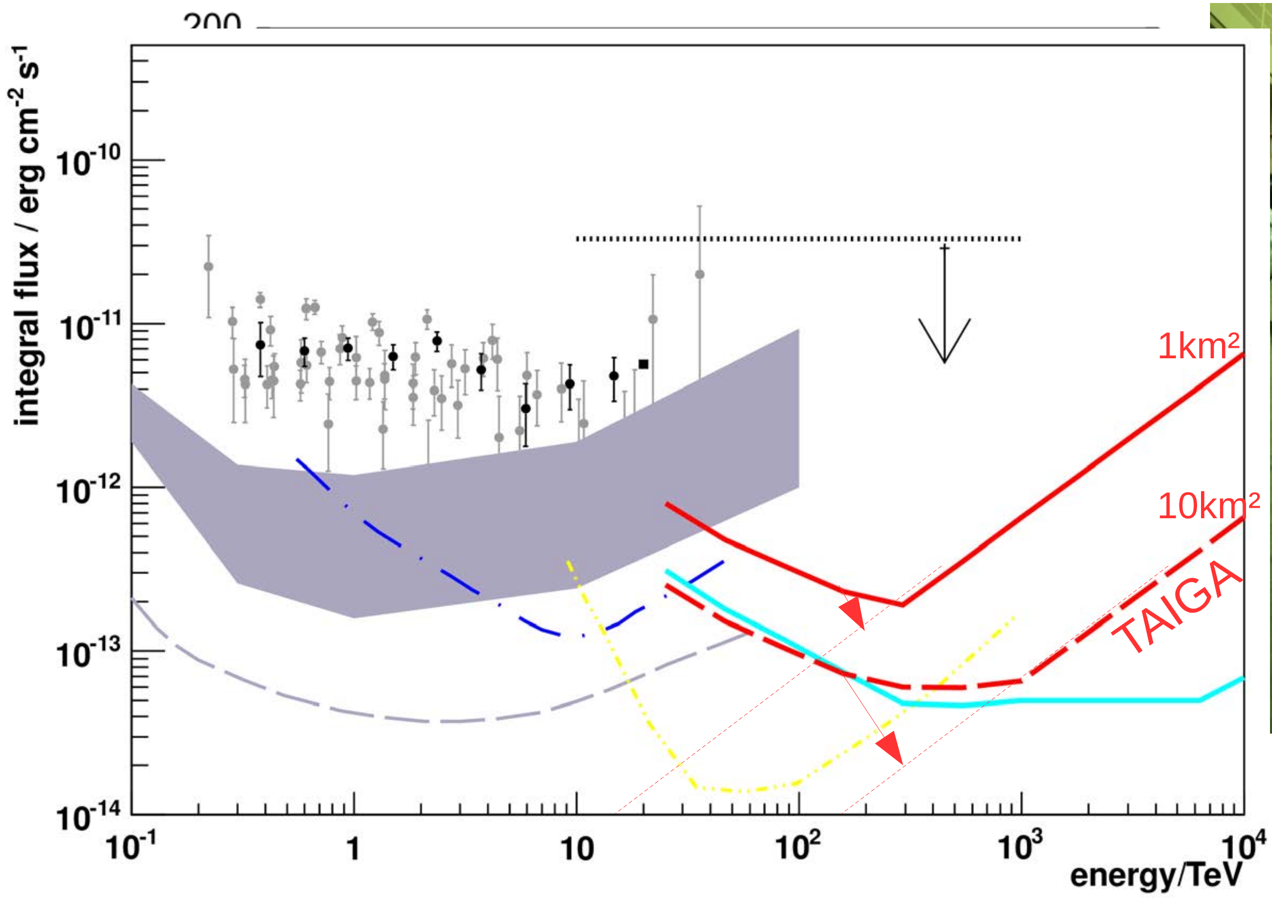
- Planned: equip 0.2% of array area with Muon detectors

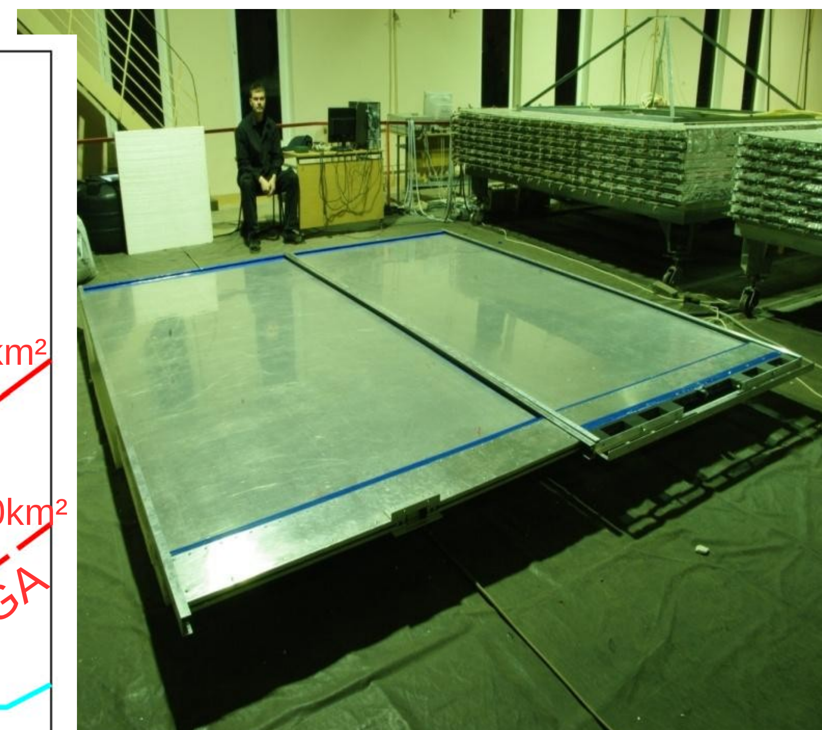




TAIGA Muon detectors

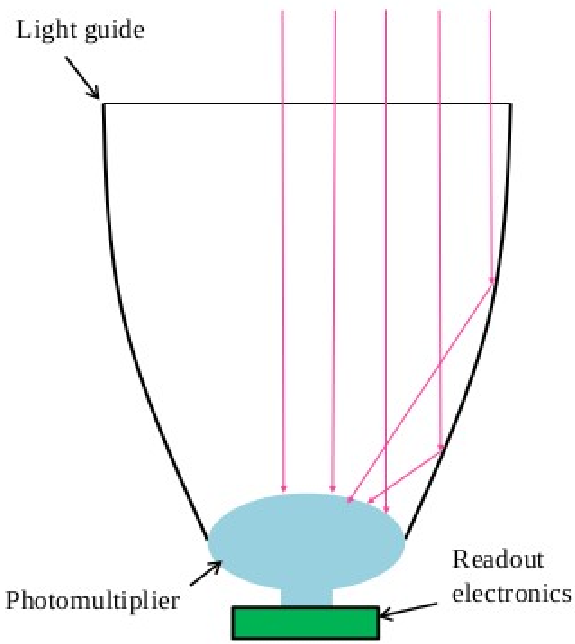
- Planned for the 1 km² stage:
  equip 0.2% of array area with Muon detectors



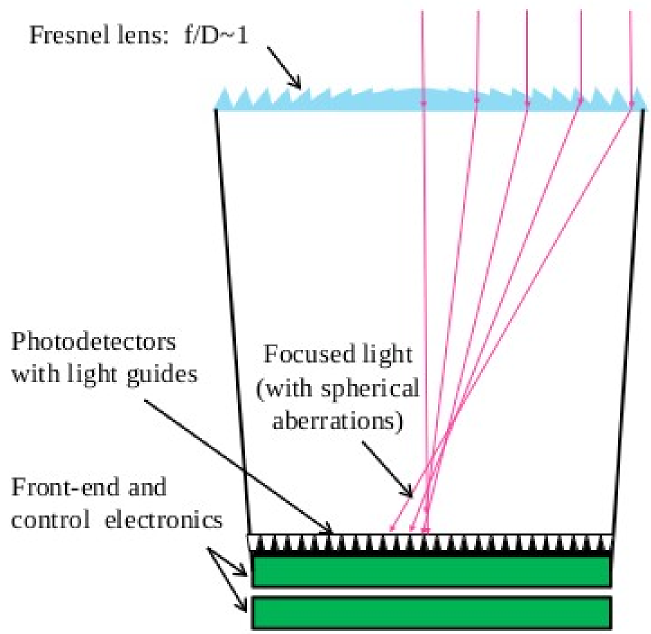


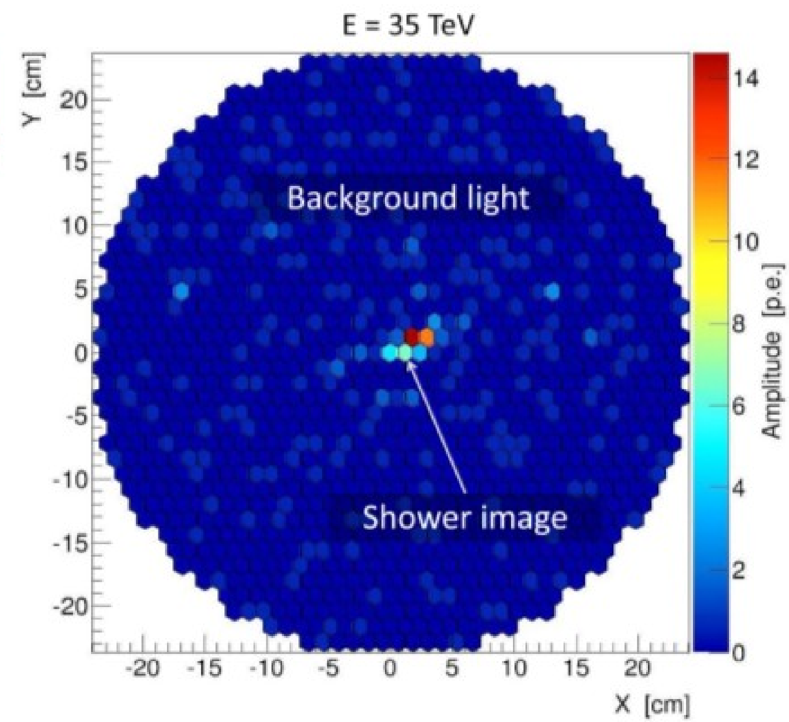
FAMOUS / ASGaRD / LoTOS

Non-imaging: HiSCORE module



Imaging: LoTOS





Similar detector size

Introducing "Minimal Imaging"

Shayduk et al. 2015, PoS ICRC 2014

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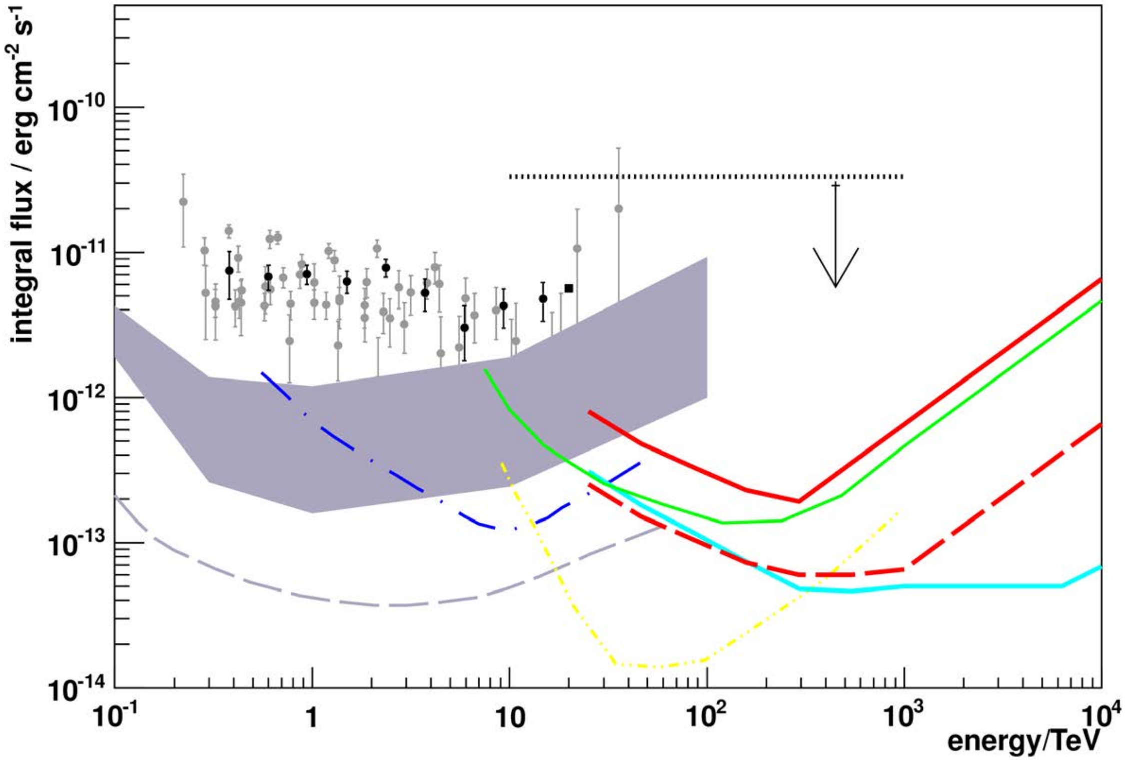
FAMOUS / ASGaRD / LoTOS

- Optical station with minimal imaging
- Acrylic Fresnel lens 0.3m radius
- 2000 SiPM camera equipped with light-guides
- 50° FoV



Shayduk et al. 2015, PoS
ICRC 2014

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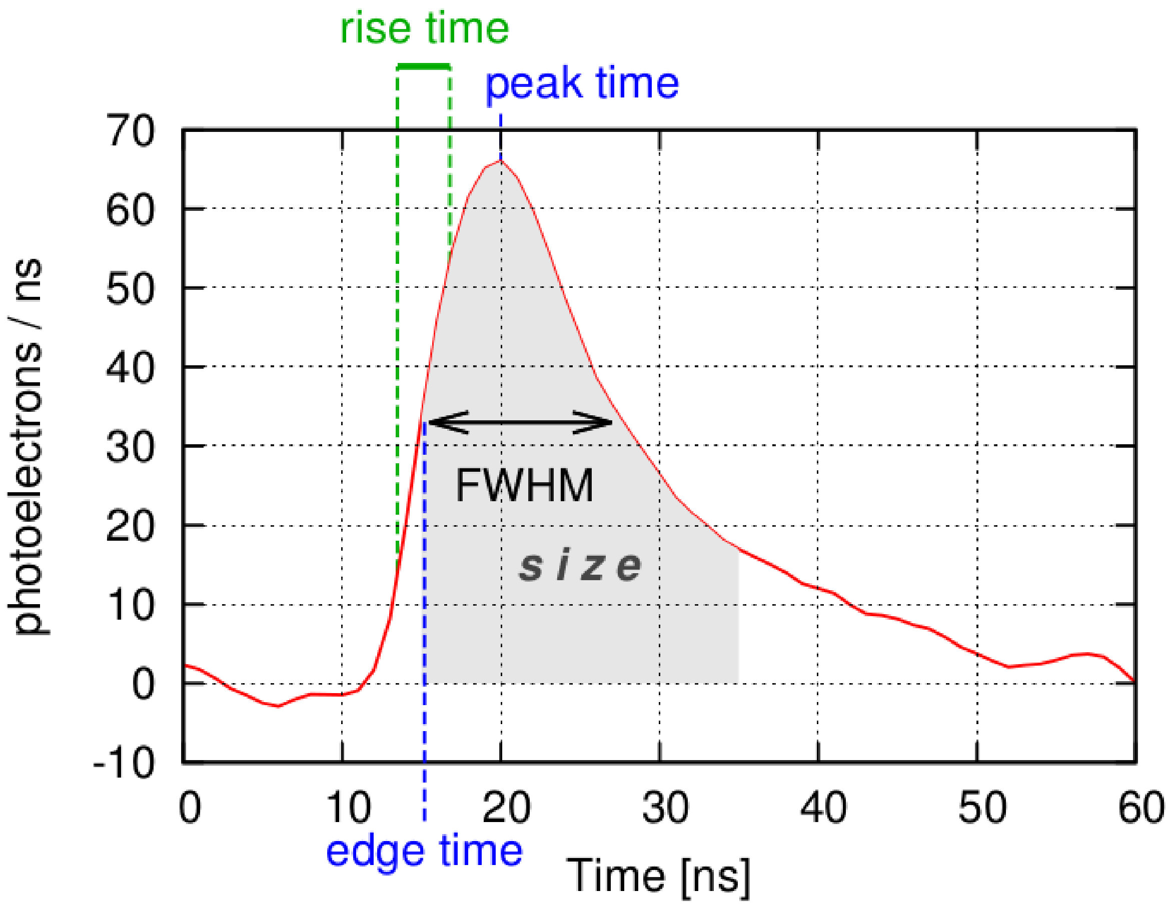
Summary

- **Different approaches to cover Multi-TeV—PeV gamma-ray regime**
- **Promising avenue: combine techniques**
  - Imaging/timing/(particles)
  - Particles/photons
- **Large arrays possible with low level of complexity**
- **Potential for opening up gamma-ray astronomy in the multi-TeV regime**

Backup slides

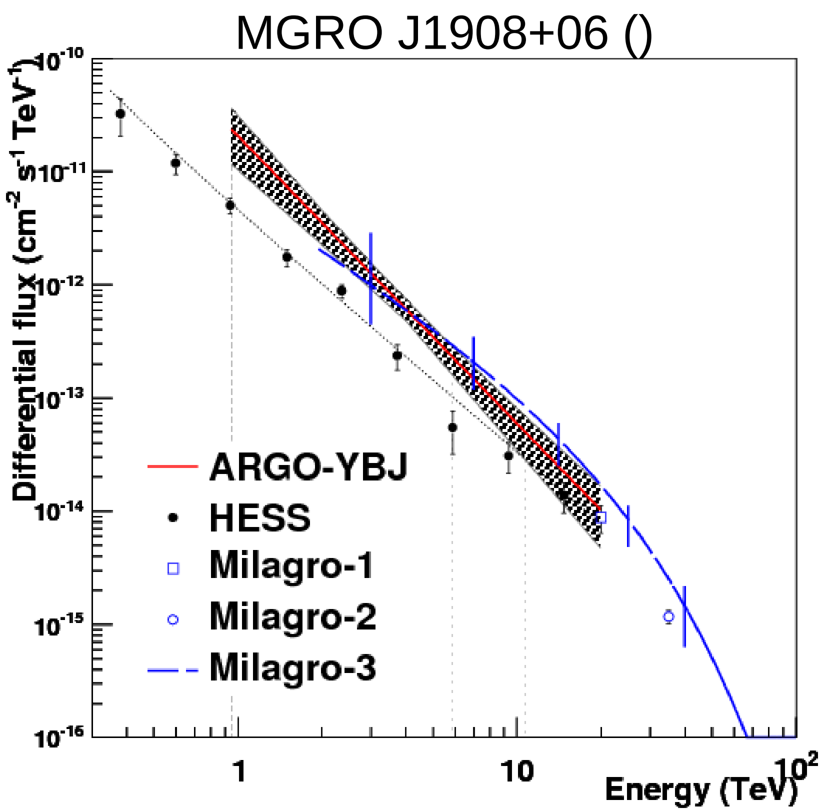
Timing of air showers

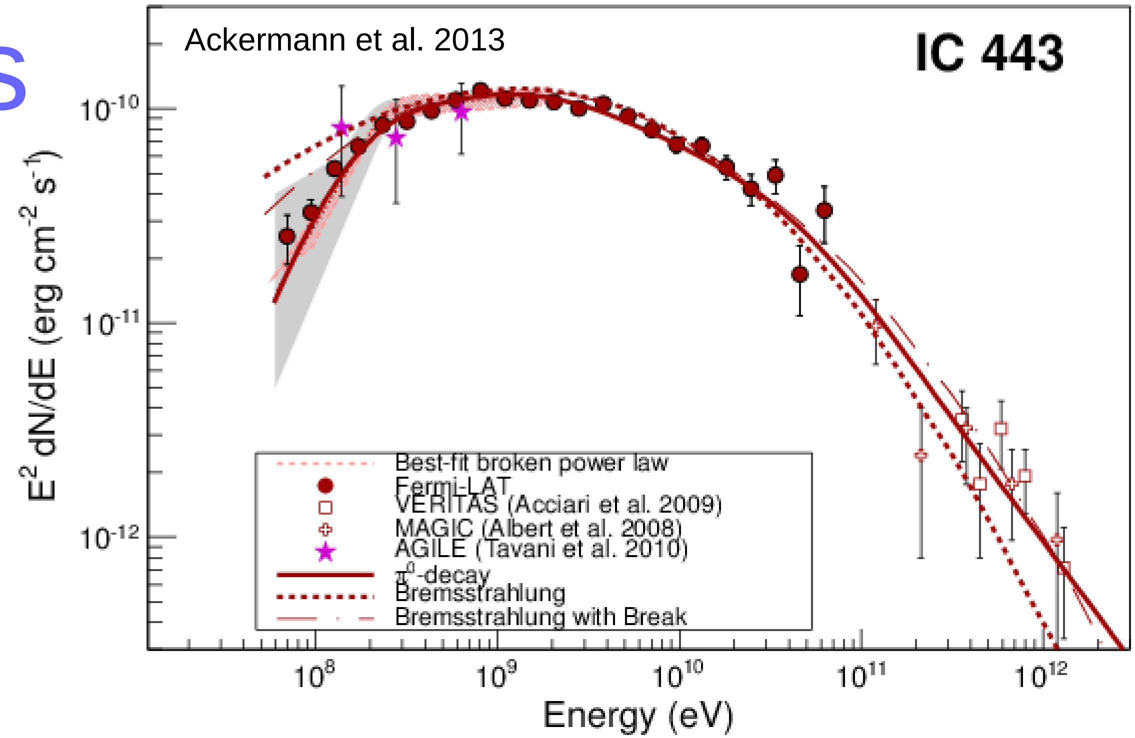
- Particle front disk width: ~30ns @ 100 m
- Cherenkov light front: disk width: <10 ns @ 100 m

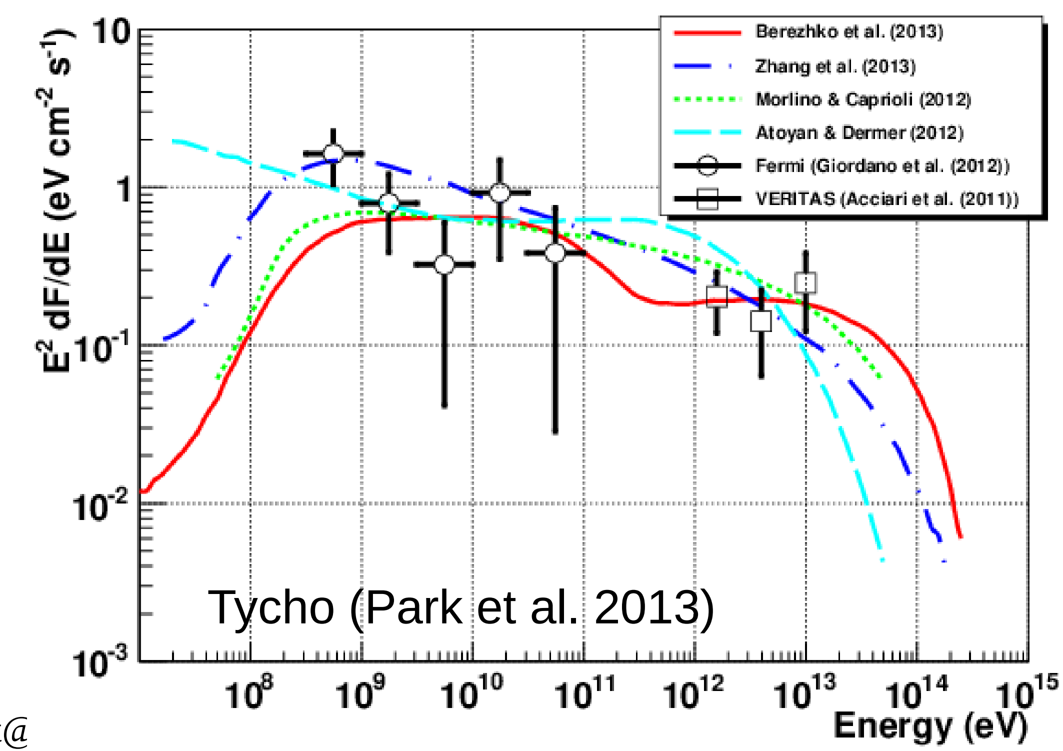


500 TeV
200 m

Galactic Gammas beyond 10 TeV

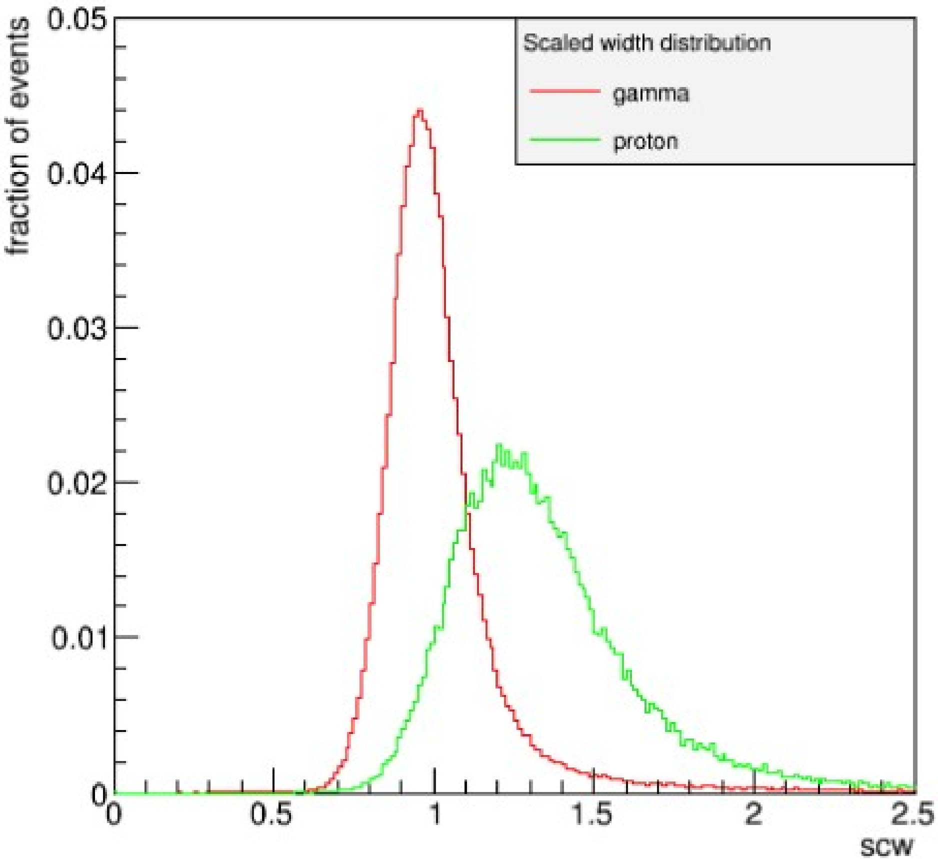






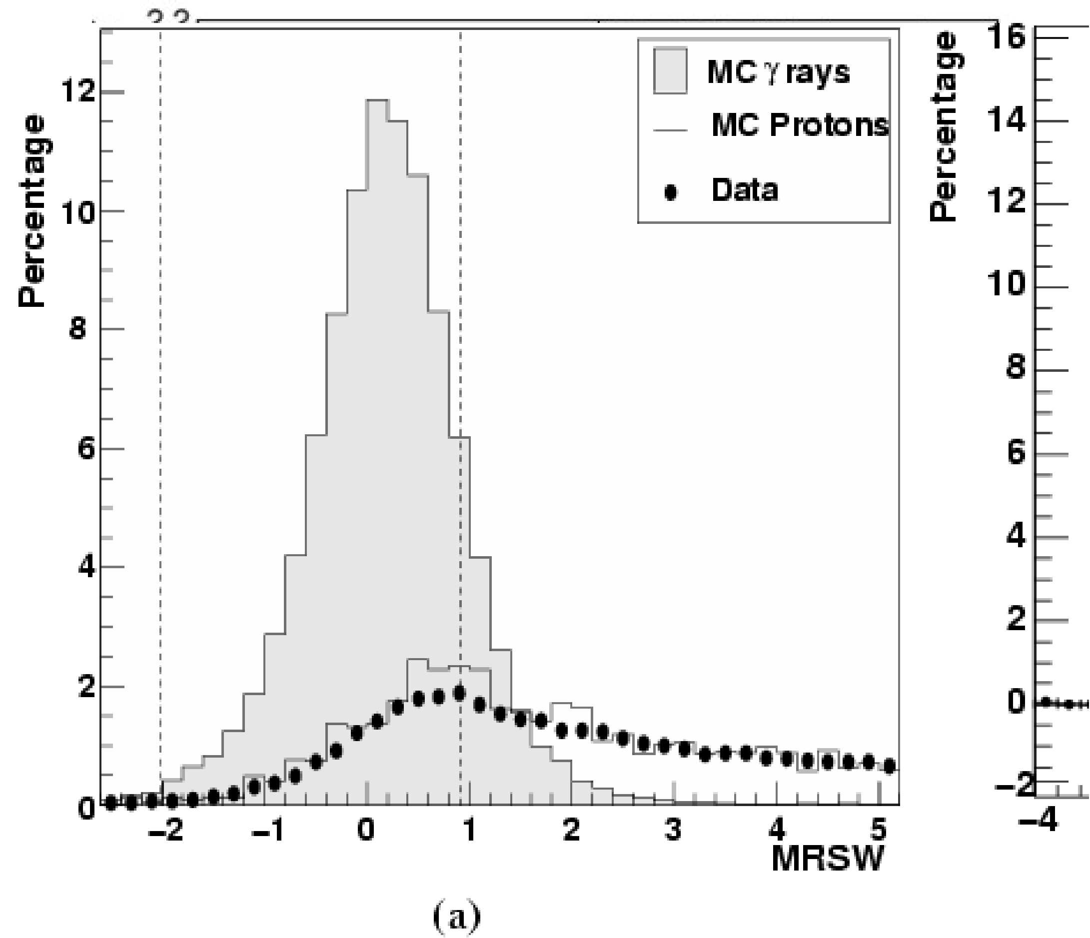
TAIGA HSCW vs. HESS MRSW

TAIGA



Q-factor ~ 2

H.E.S.S.



Q-factor ~ 3

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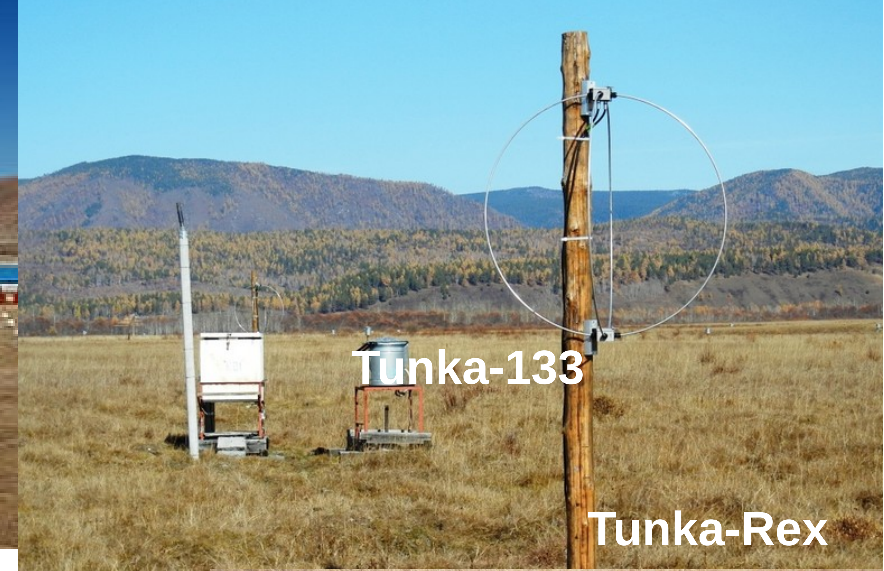
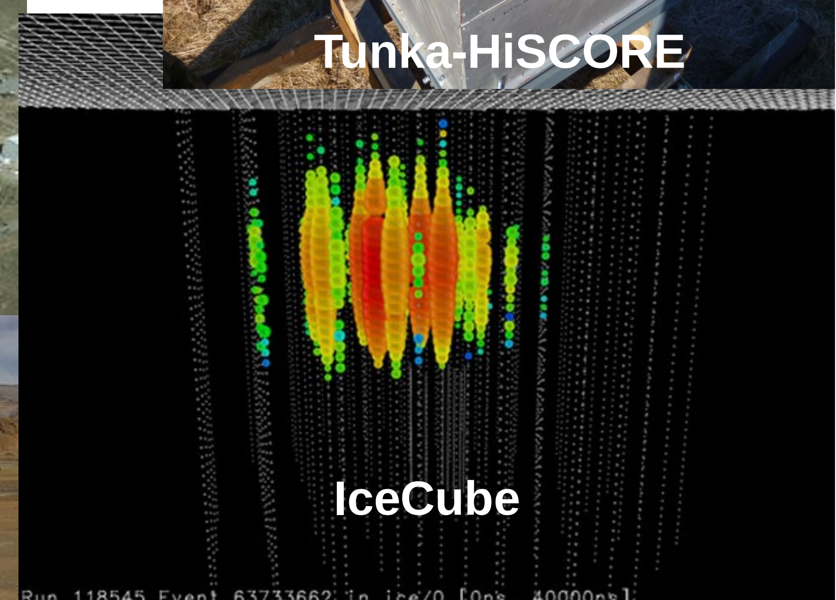
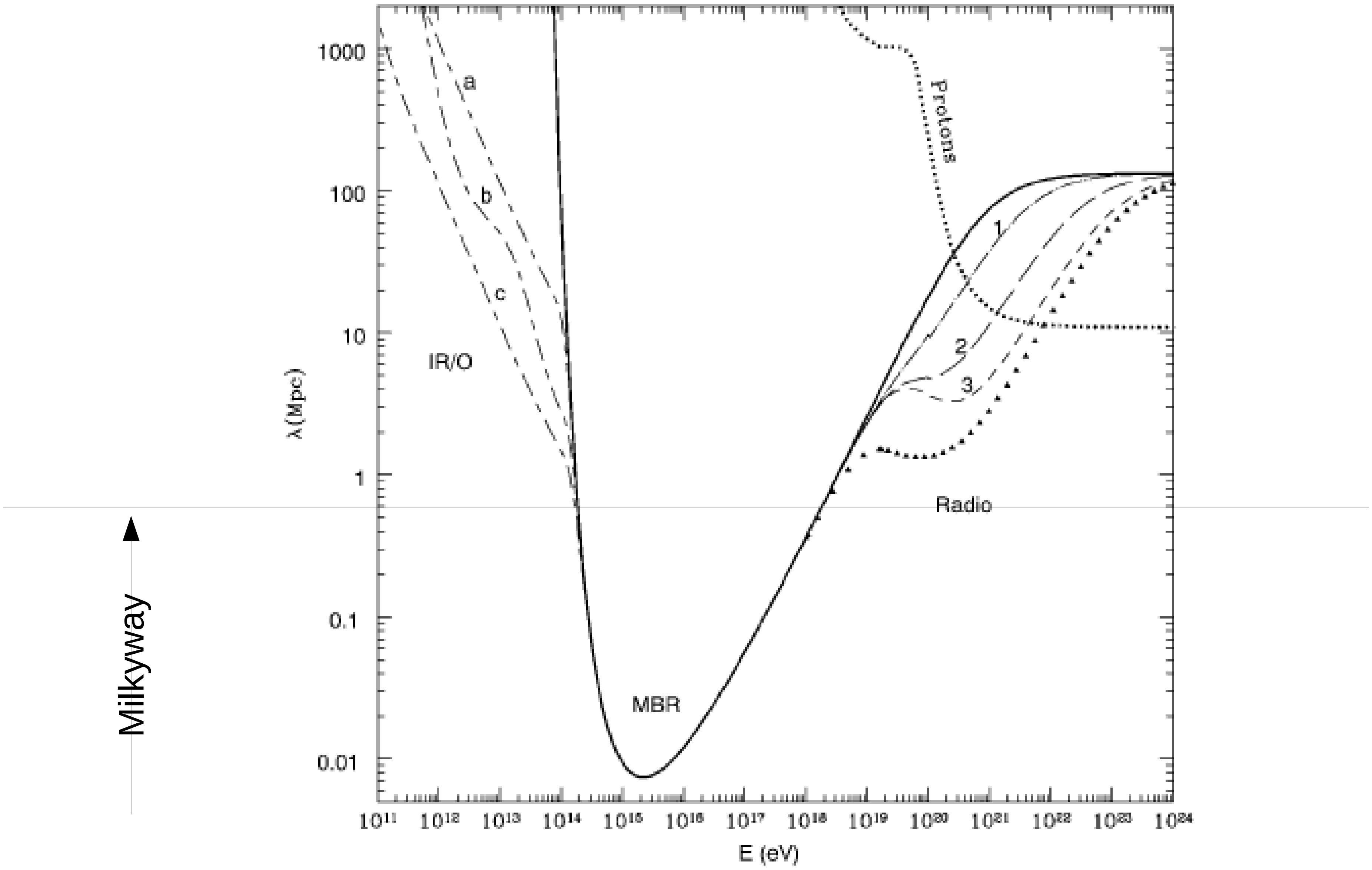
Timing arrays





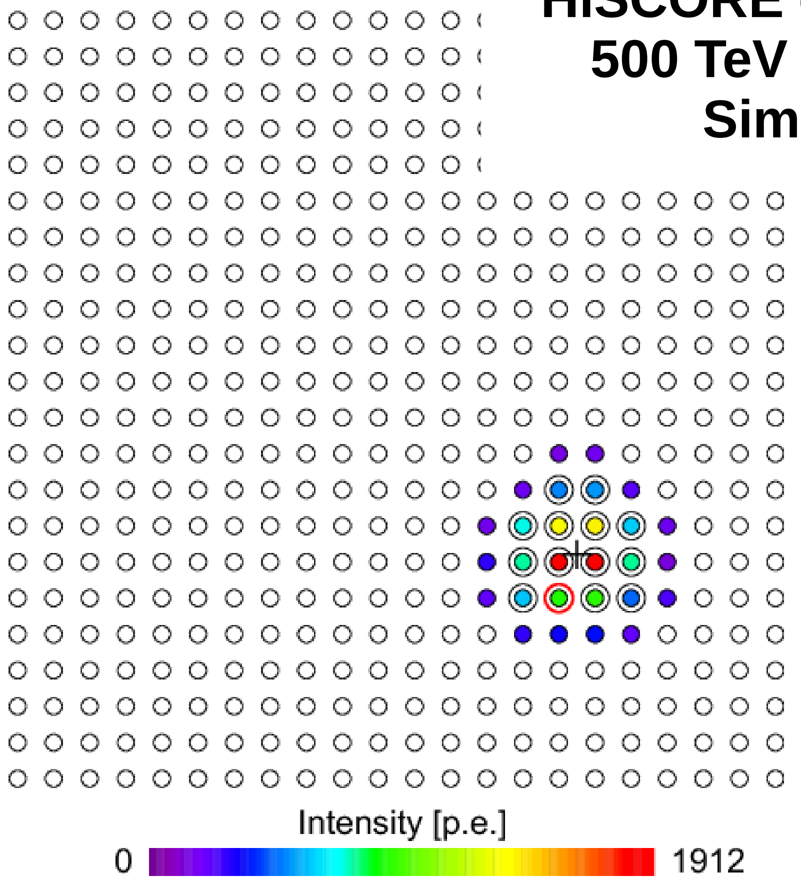
Gamma-ray astronomy

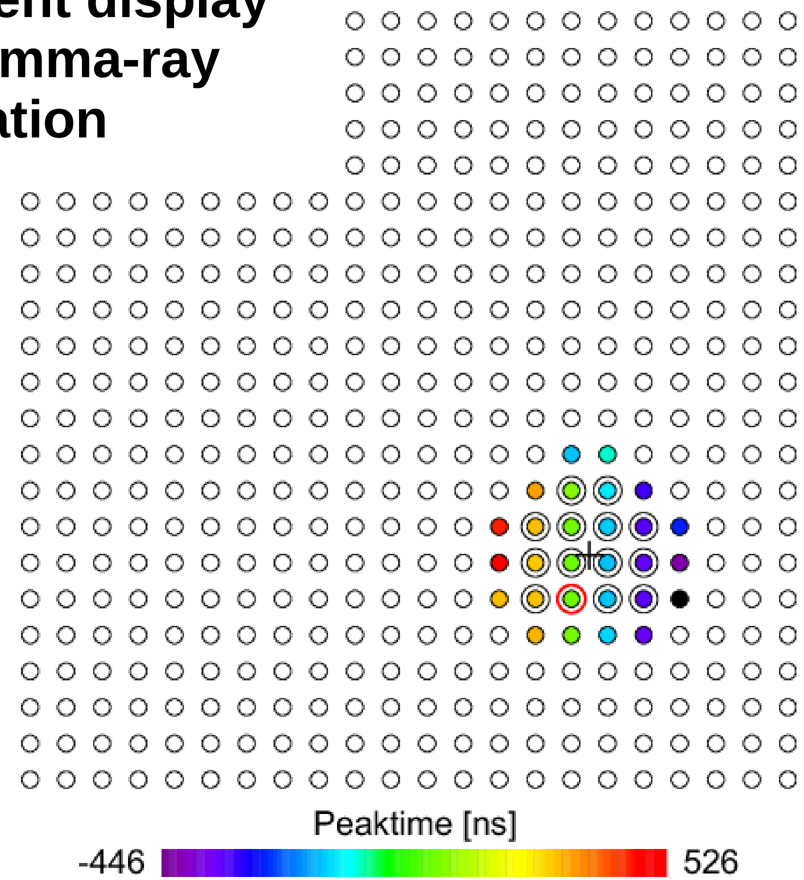


Timing Reconstruction

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

HiSCORE event display
500 TeV gamma-ray
Simulation





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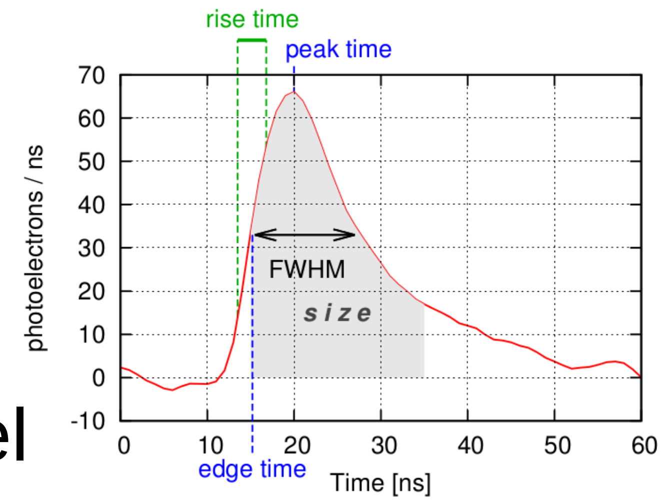
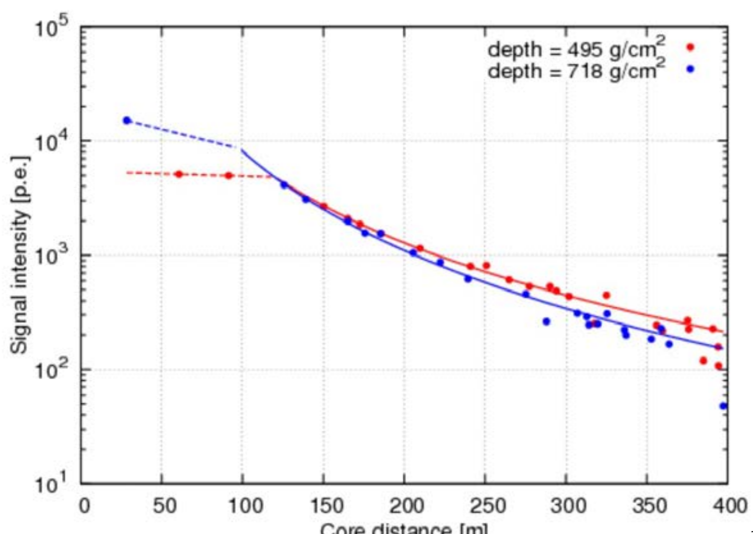
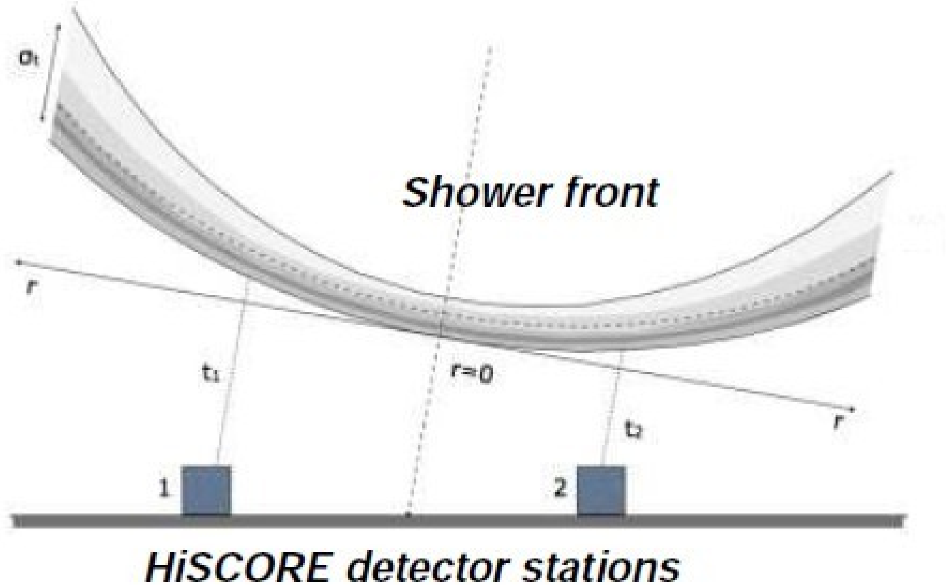
Timing Reconstruction

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

- 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

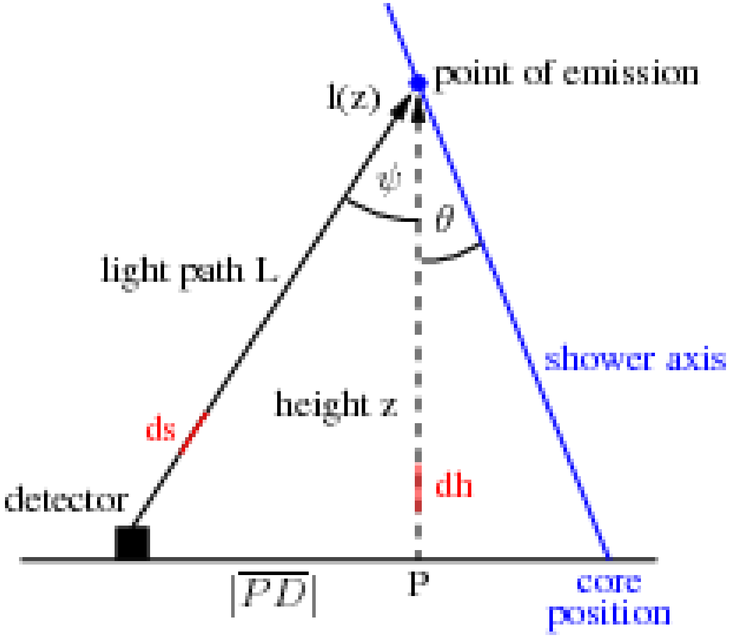






Arrival time model

2013NIMPA.712..137H



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

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

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

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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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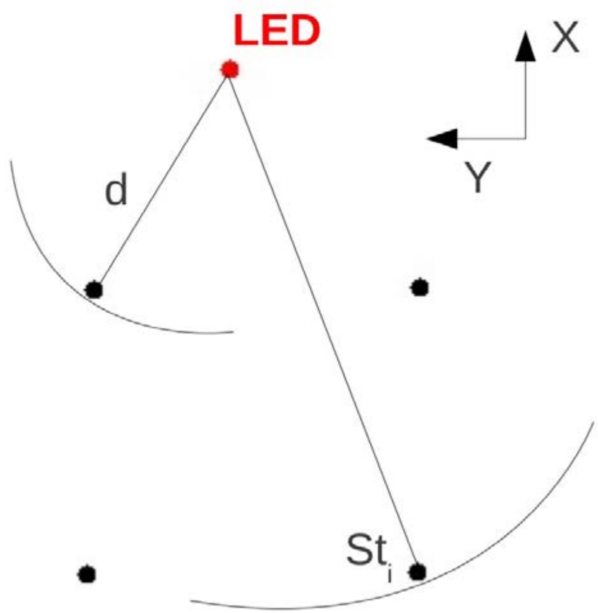
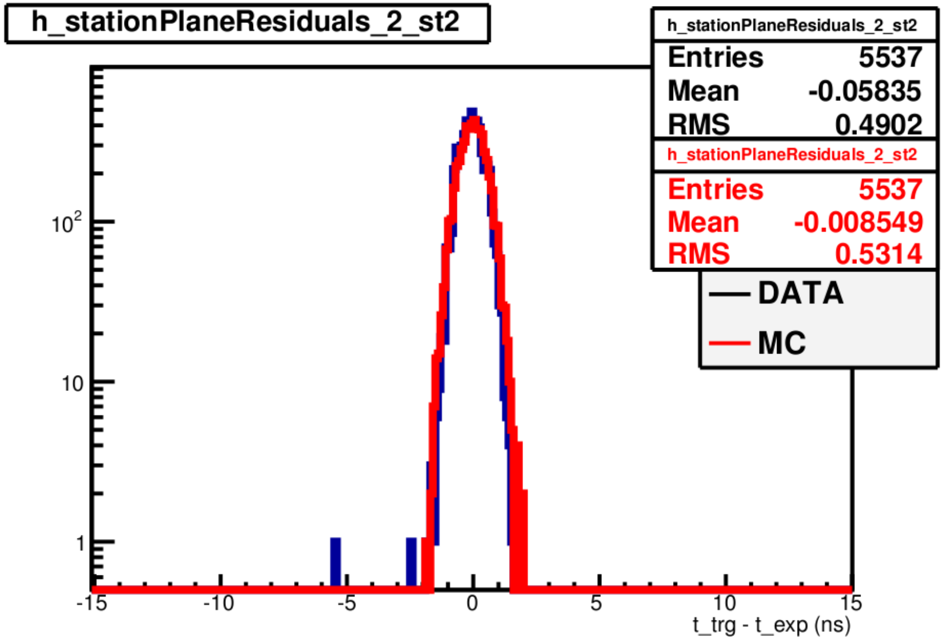
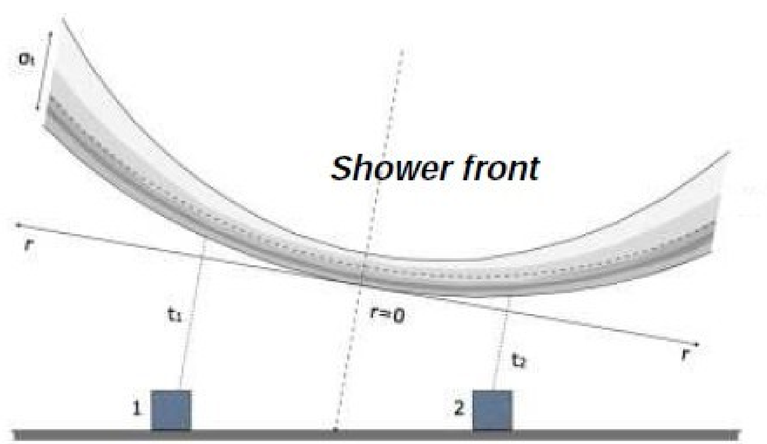
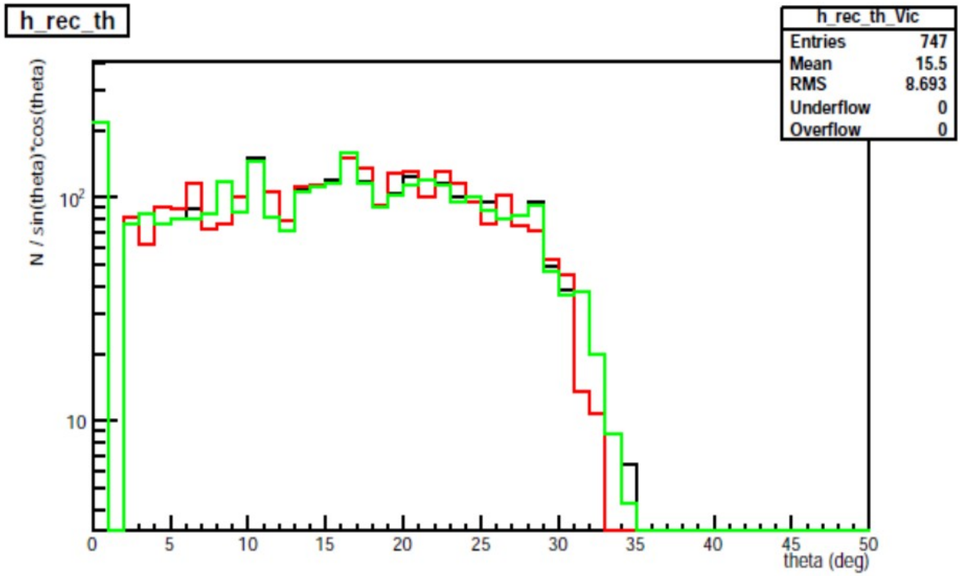
Time calibration







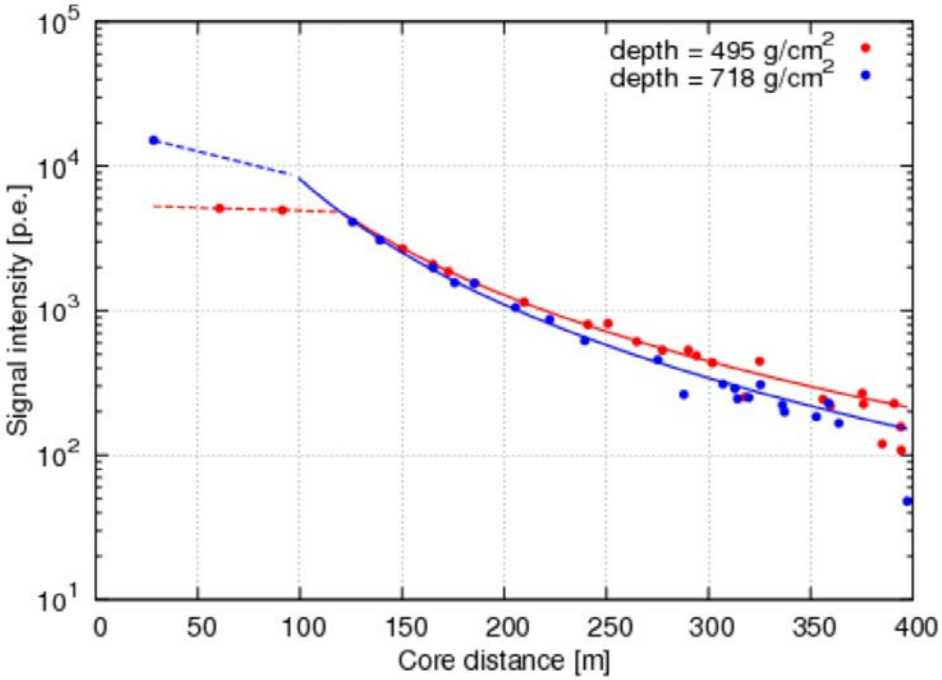
HiSCORE detector stations



Energy determination

Energy → light density

Q(x) = LDF at x m



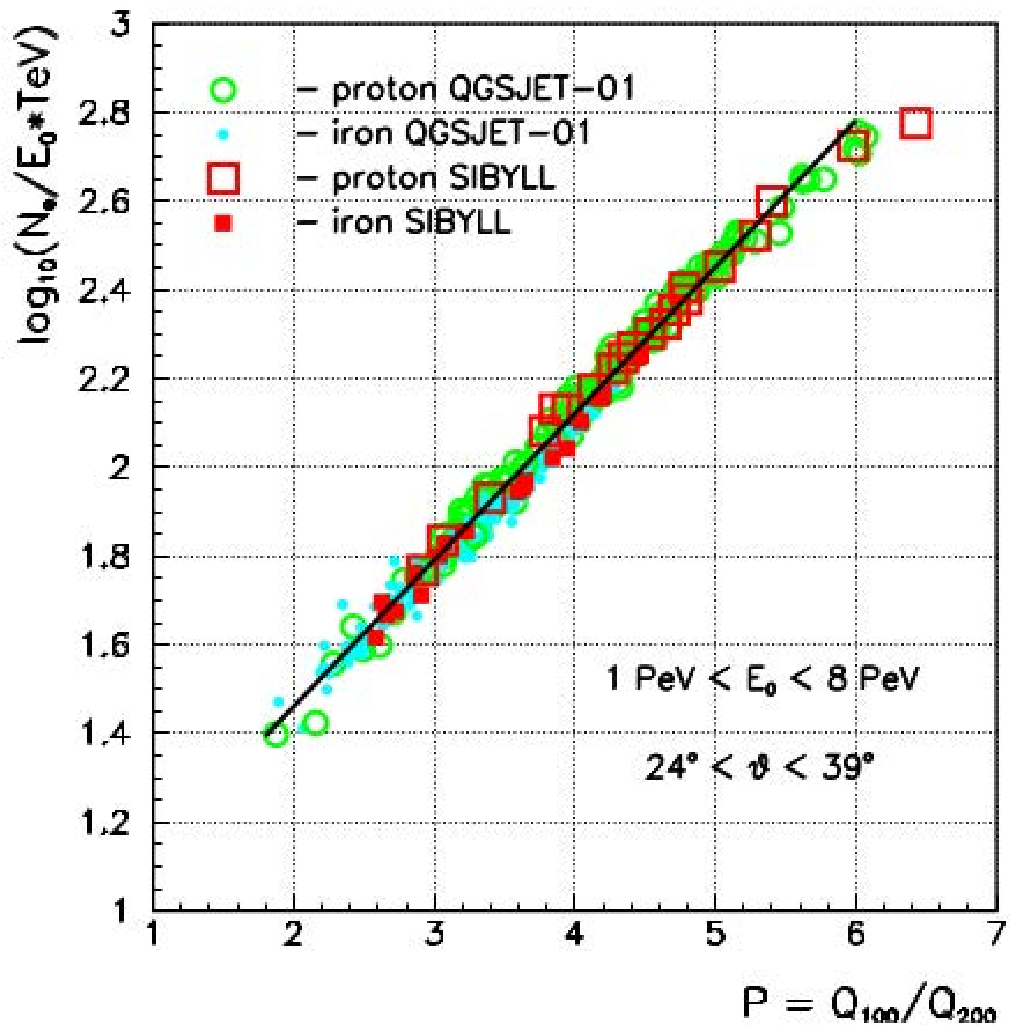


Figure 2: N_e/E_0 vs P

2012NIMPA.692...98B

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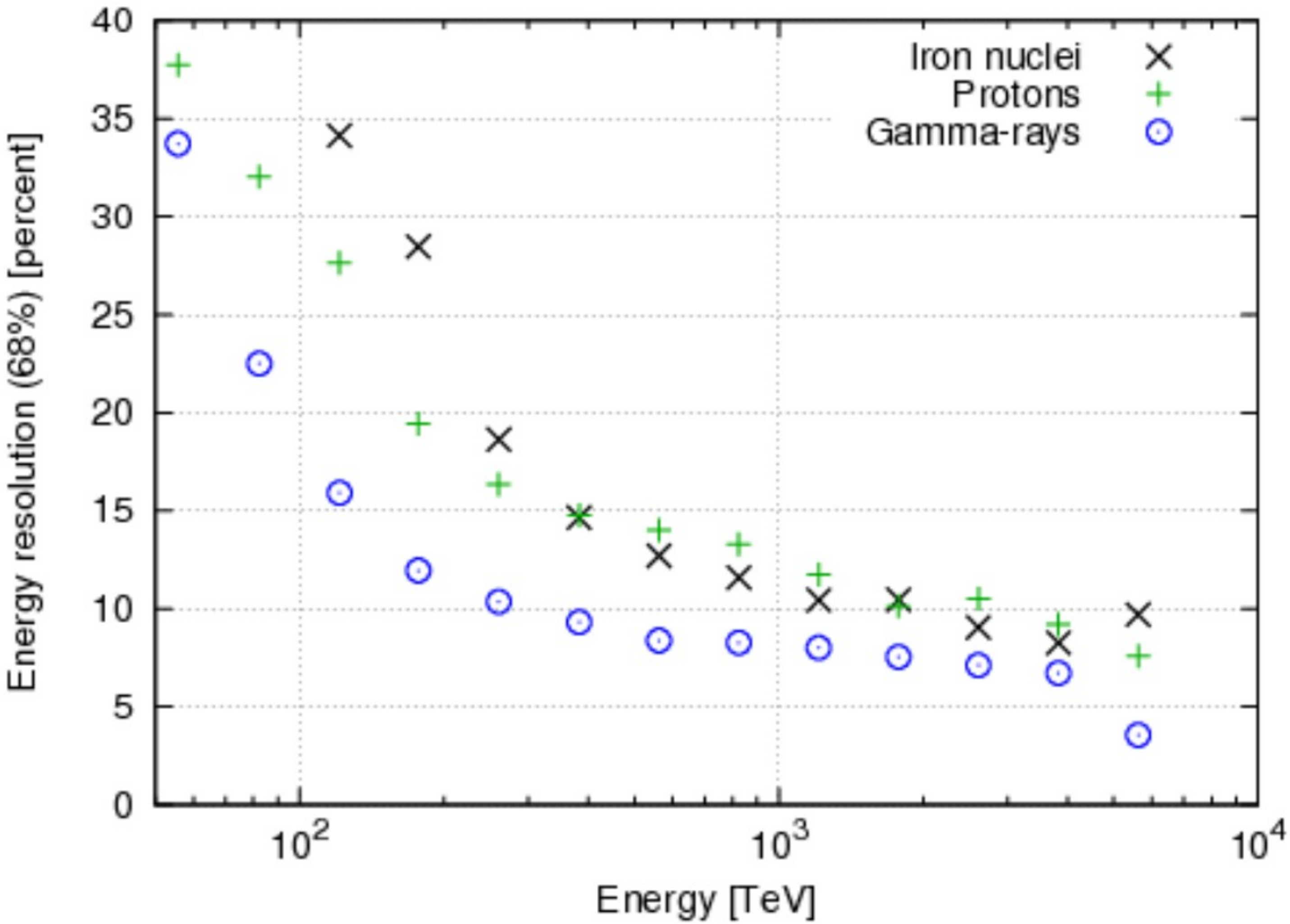
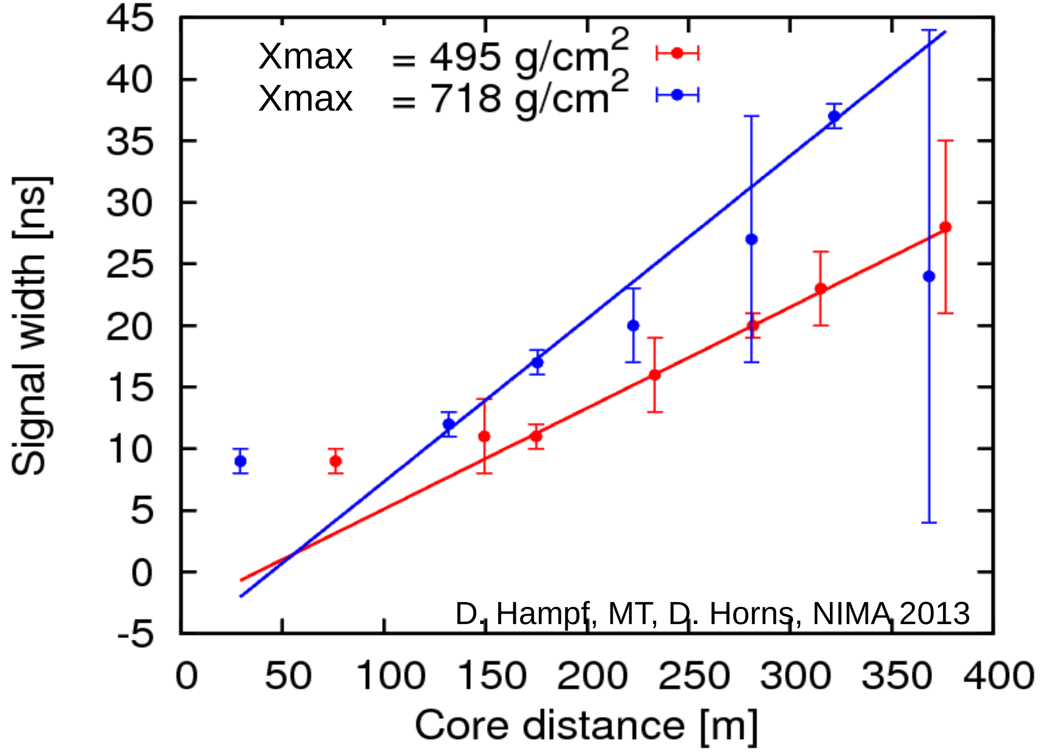
Energy determination

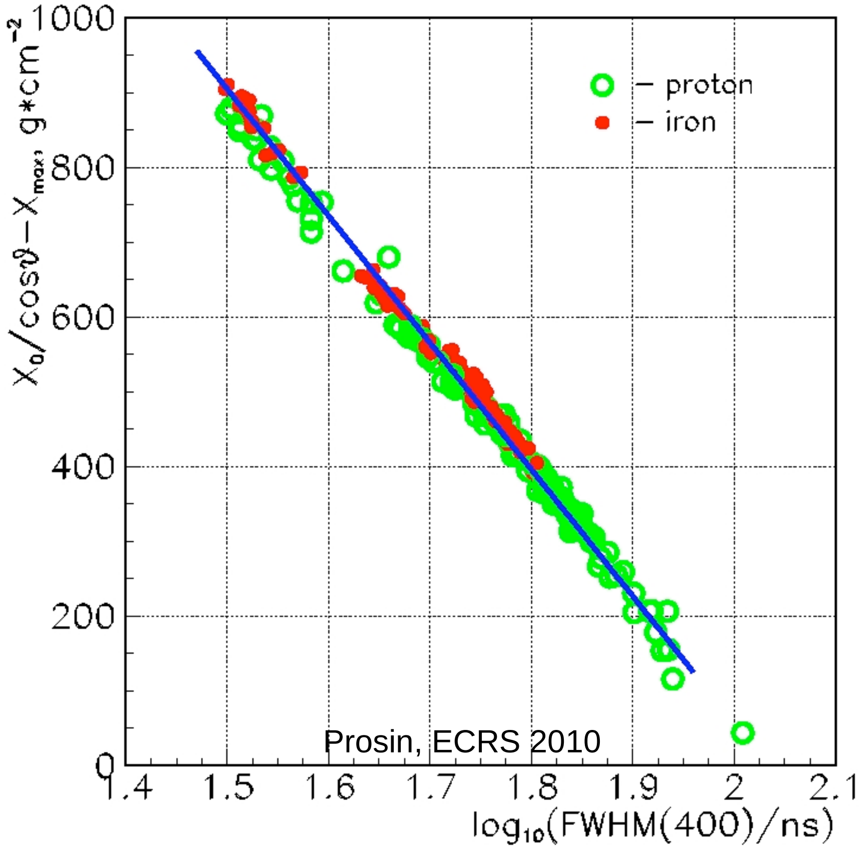
HiSCORE simulation



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





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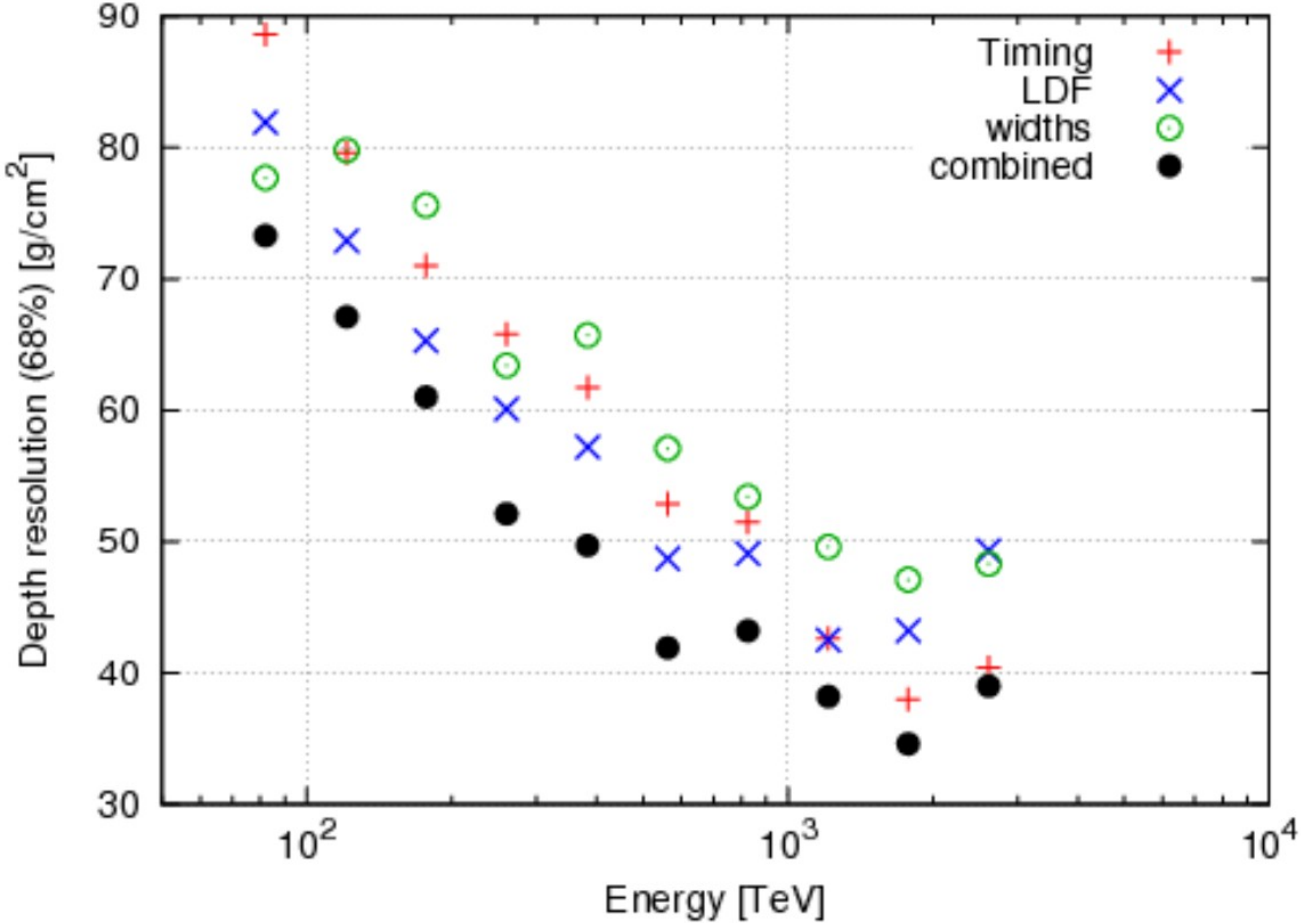
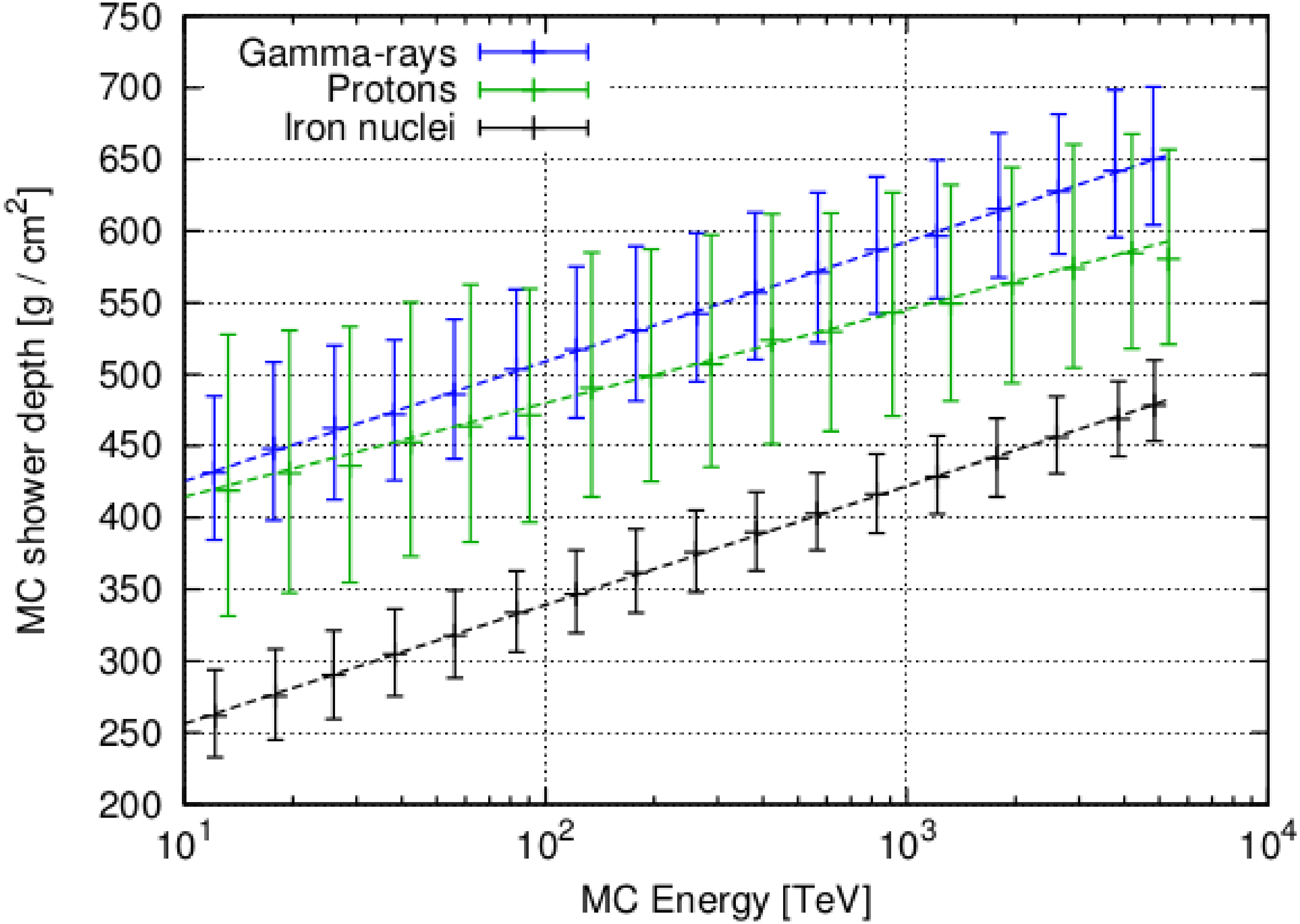
Shower maximum

HiSCORE Simulation



Particle separation Xmax vs. E



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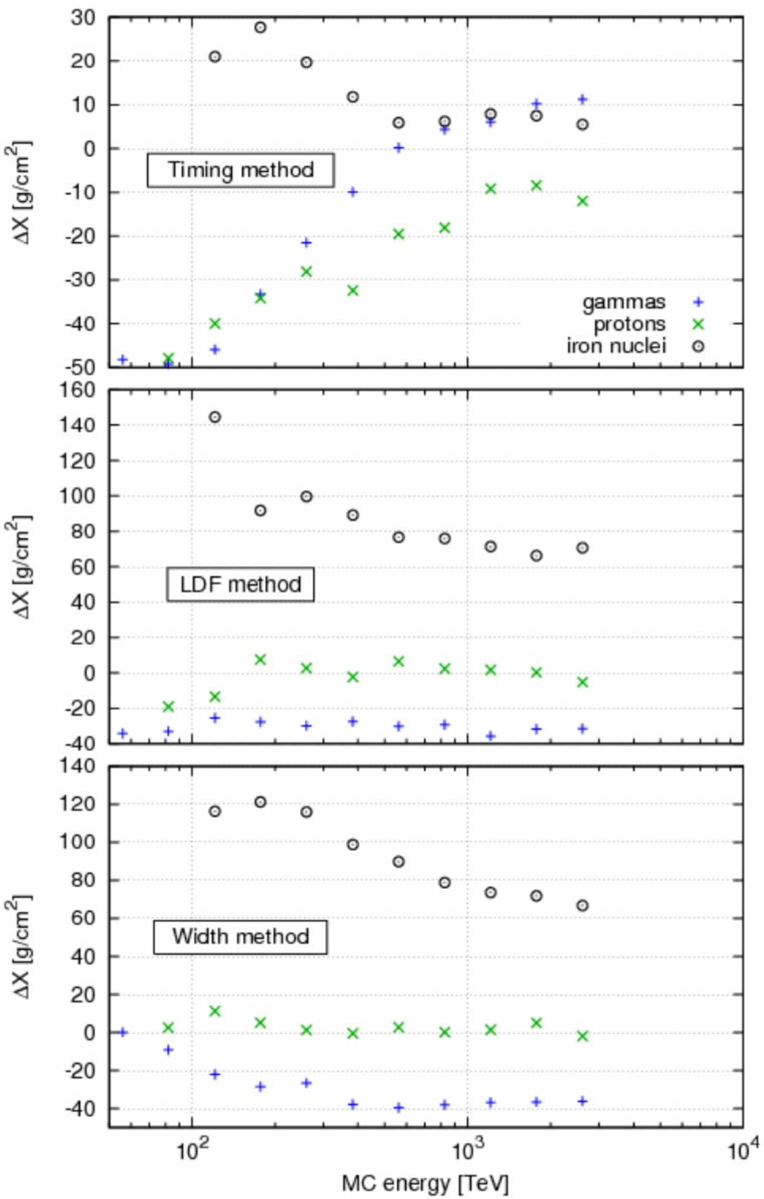
Gamma-hadron separation

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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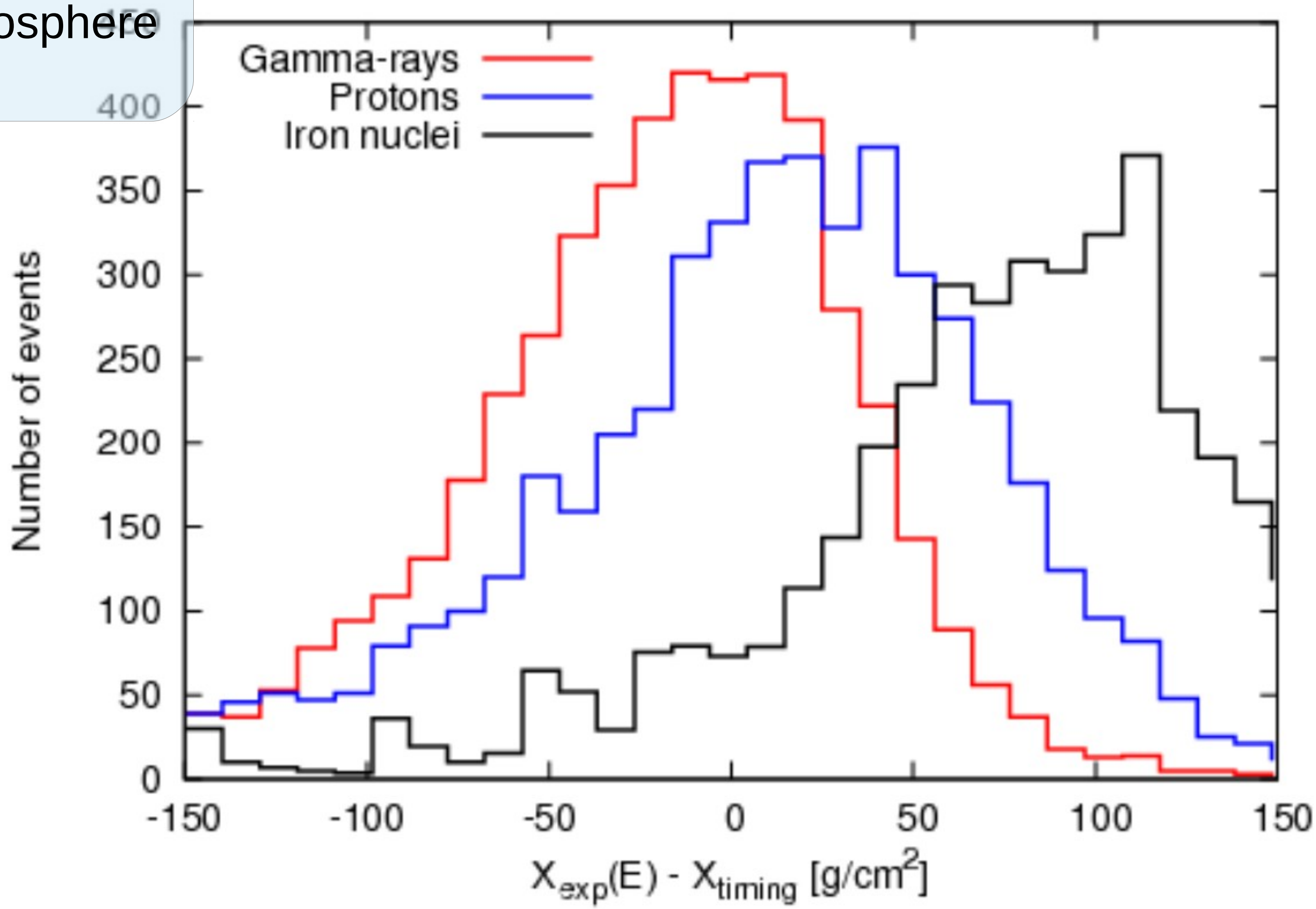
Particle separation

Lighter particles develop
Higher up in atmosphere



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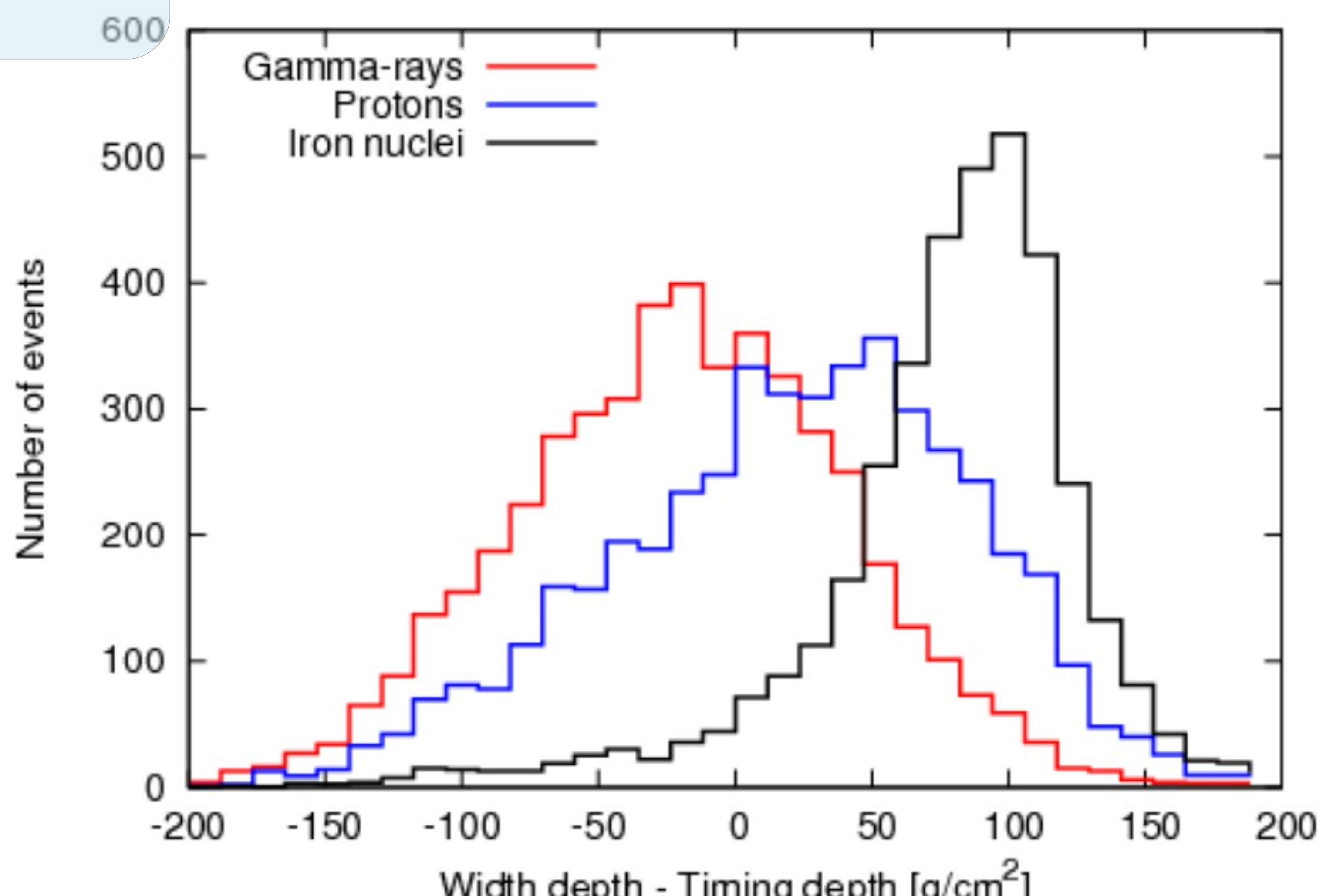
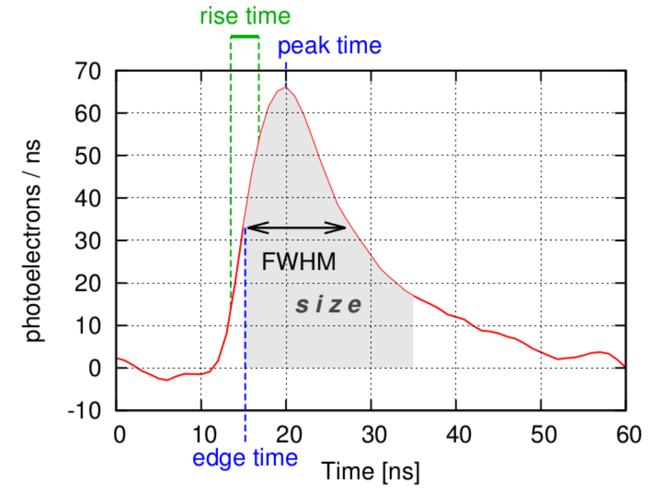
Particle separation (2)

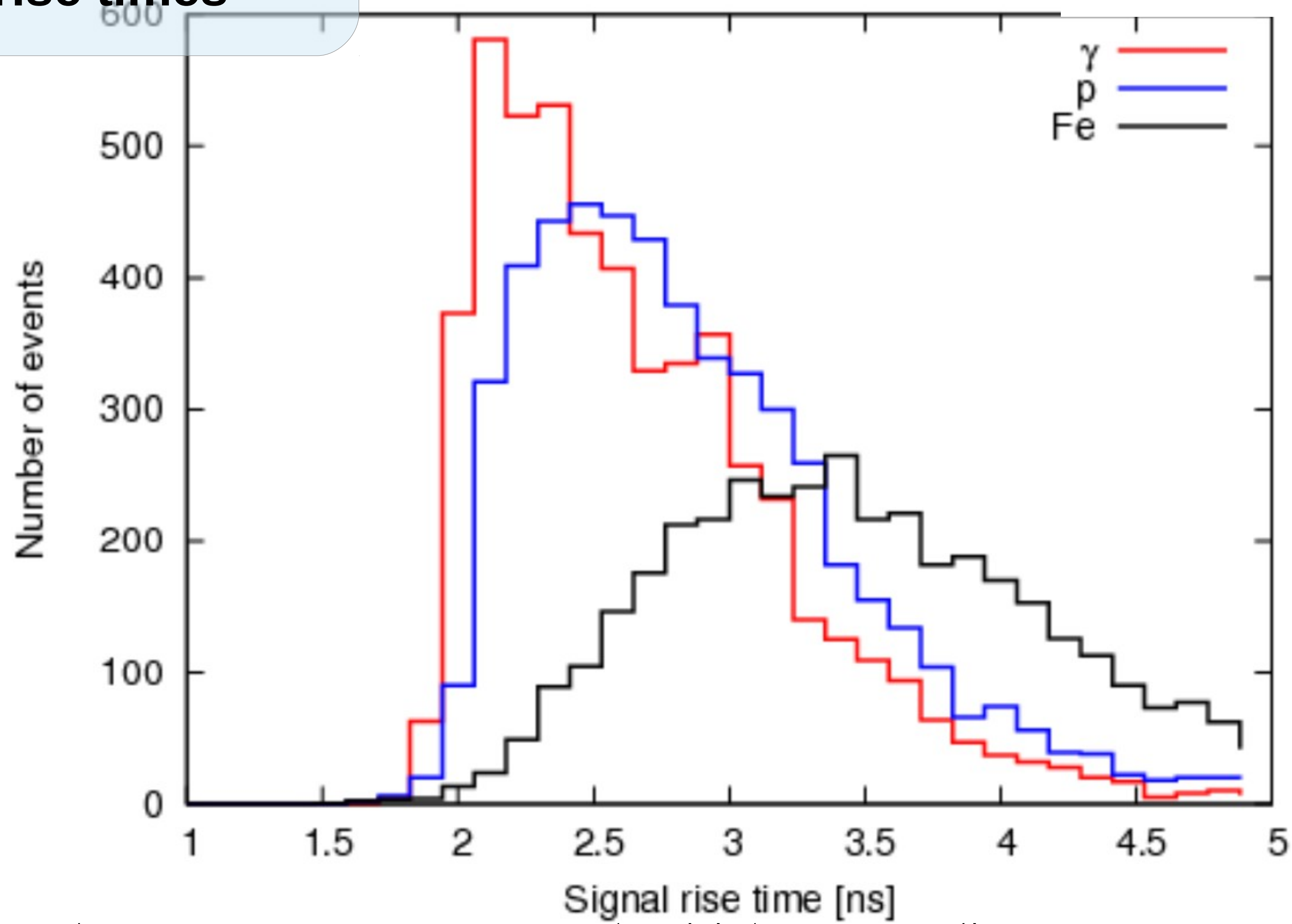
Systematic Xmax difference
Time width and timing model



Particle separation timing



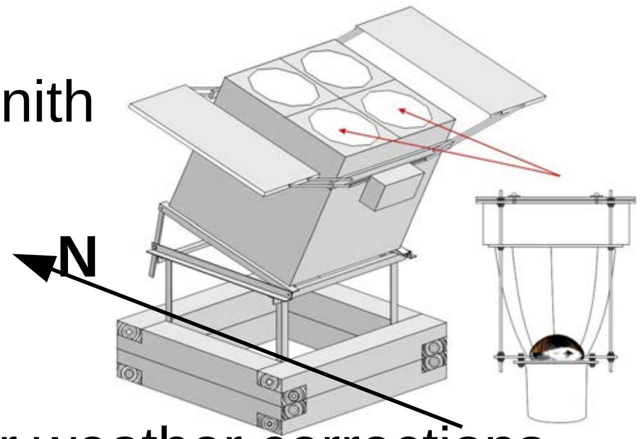
Systematic difference
Cherenkov signal
rise times



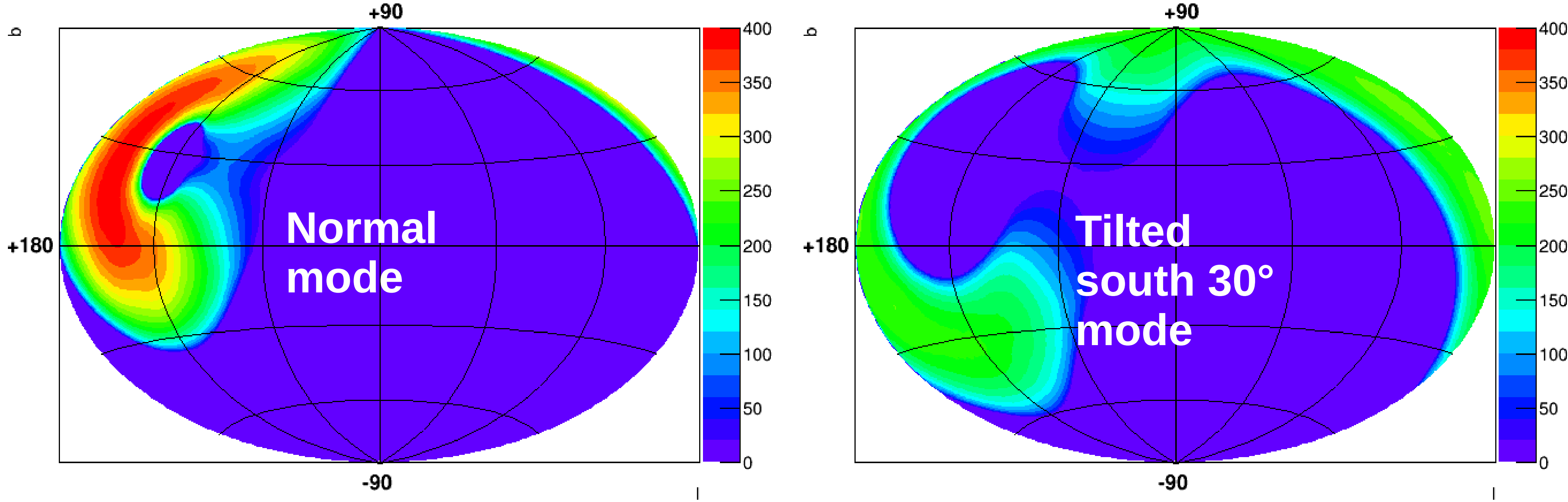
Sky coverage

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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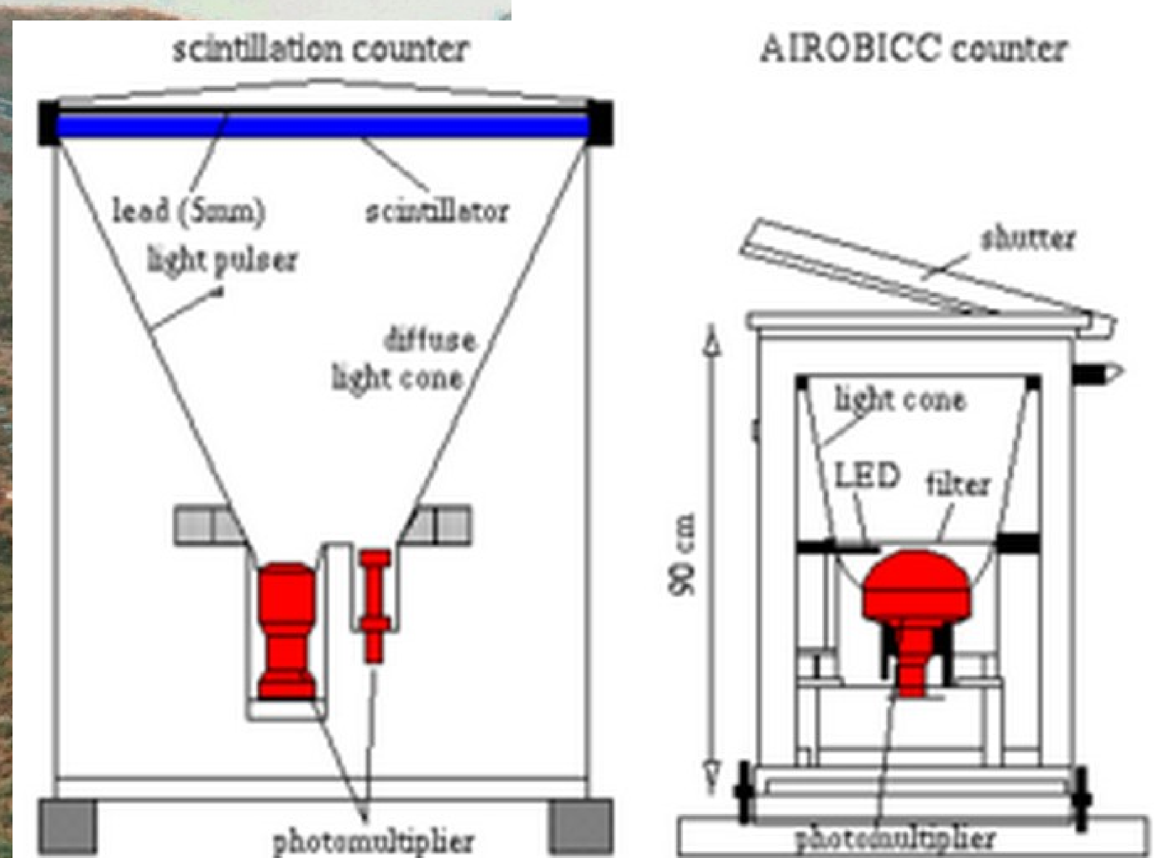
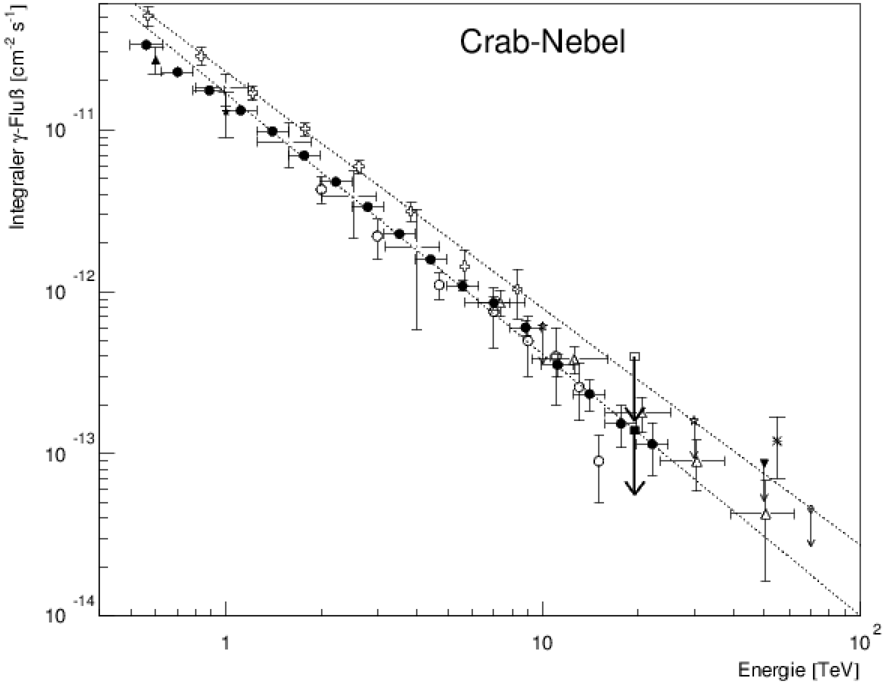
Past experiments

- Themistocle
- AIROBICC



AIROBICC results

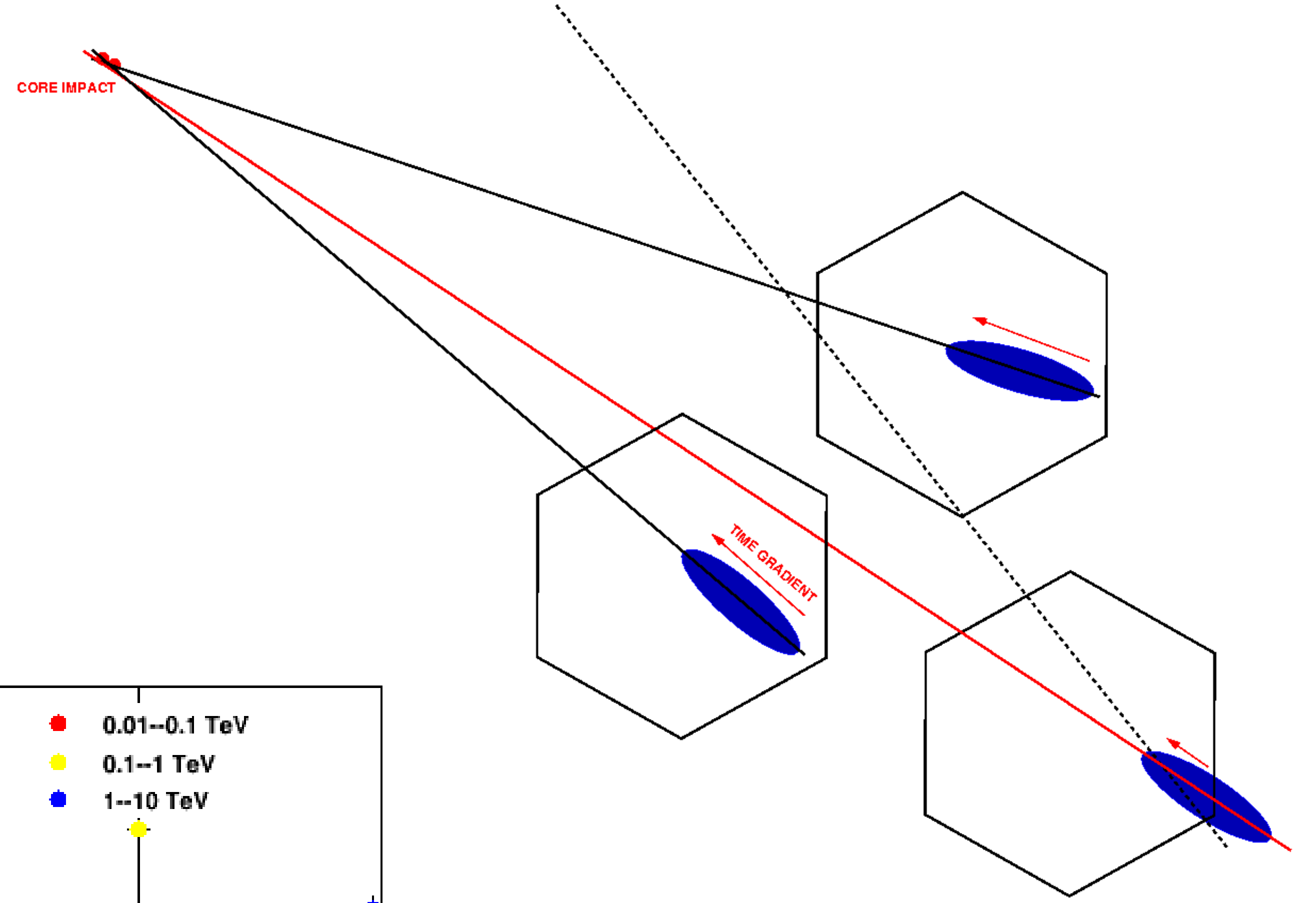


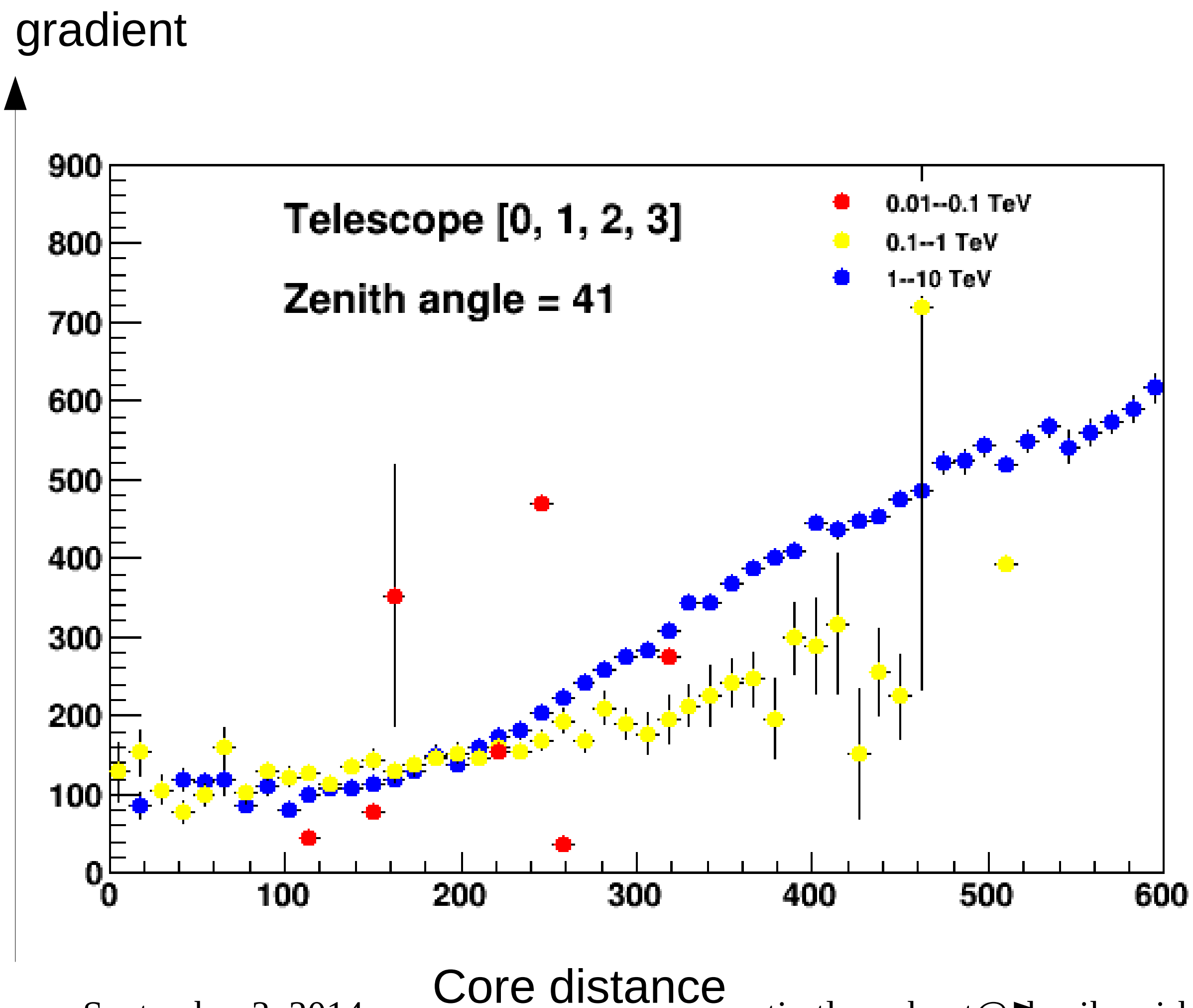
Nr.	Objekt	N_{QB}	$\hat{N}_{QB}$ $(=\alpha \cdot N_{BG})$	N_{OG}	S_{DC} [σ]	$S_{burst, exp}$ [σ]	$S_{var, kol}$ [σ]	$E_{thr, \gamma}$ [TeV]	Φ_{OG} $[10^{-13} cm^{-2} s^{-1}]$
1	GRS1915	100 (1325)	106,1 (1318,1)	13,5	**−0,57** (0,19)	−2,19	1,92	20,3	1,8
2	Cyg X-3	125 (1806)	133,3 (1739,4)	14,3	**−0,71** (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

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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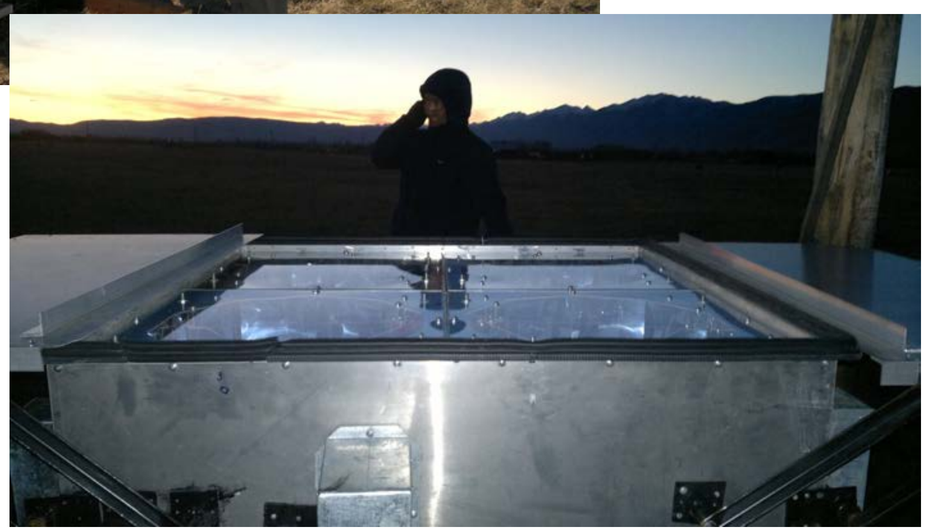
Tunka HiSCORE Status

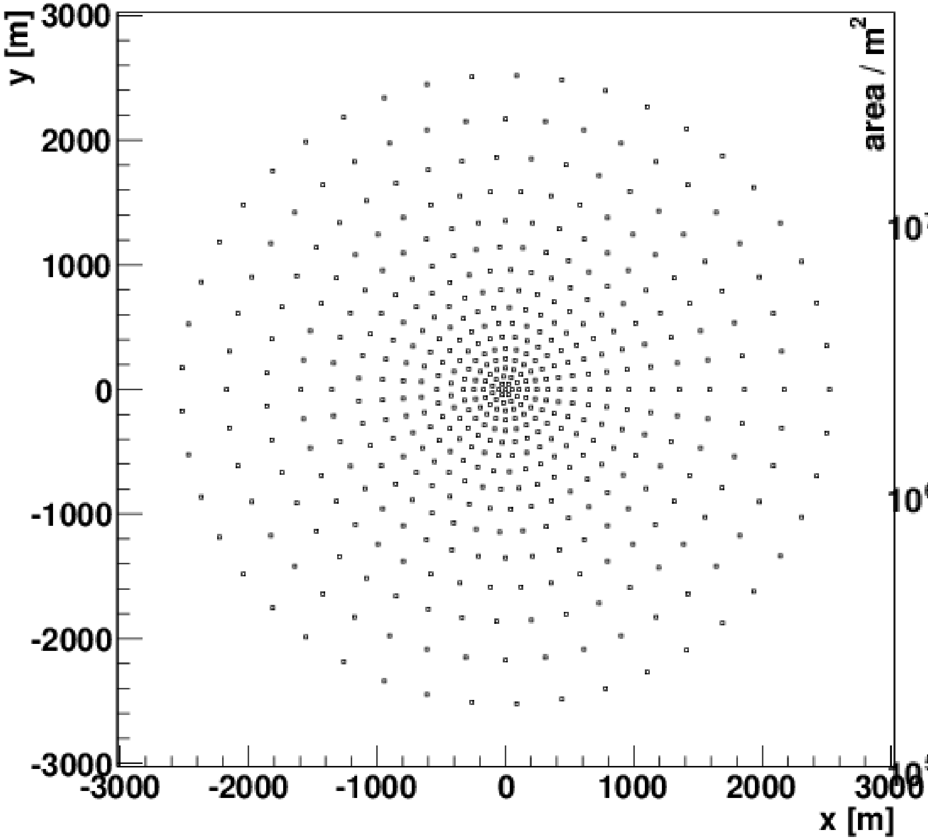
Optical station

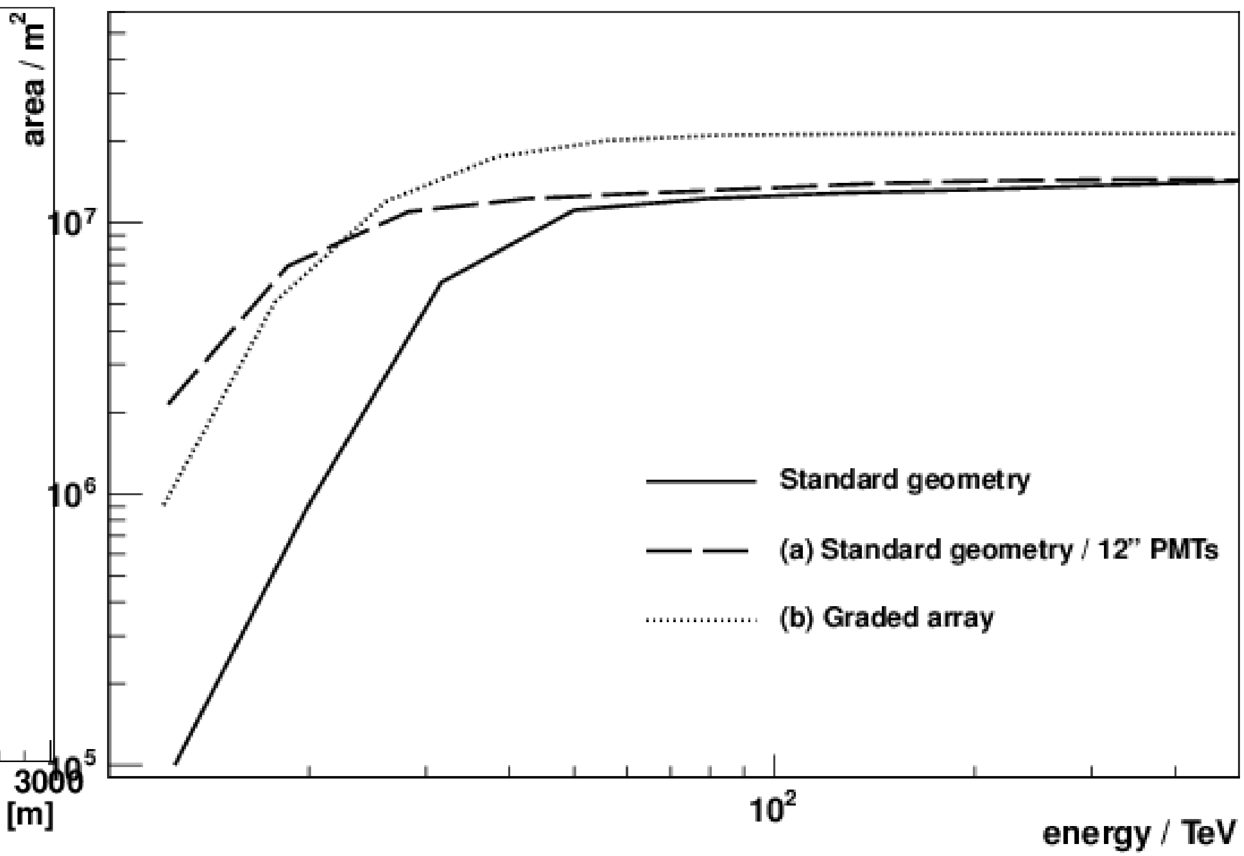
Electronic box



Array Optimization HiSCORE

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





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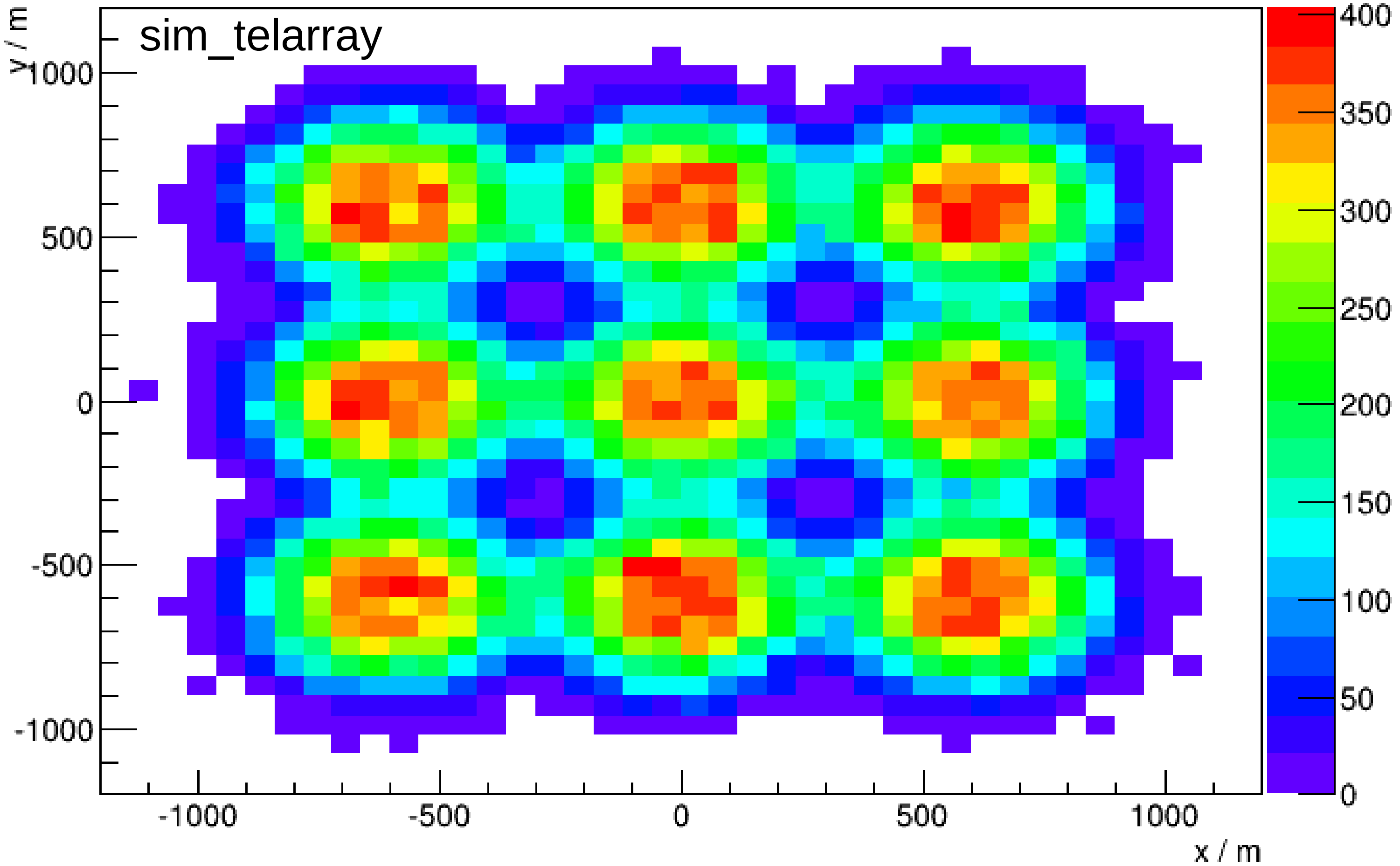
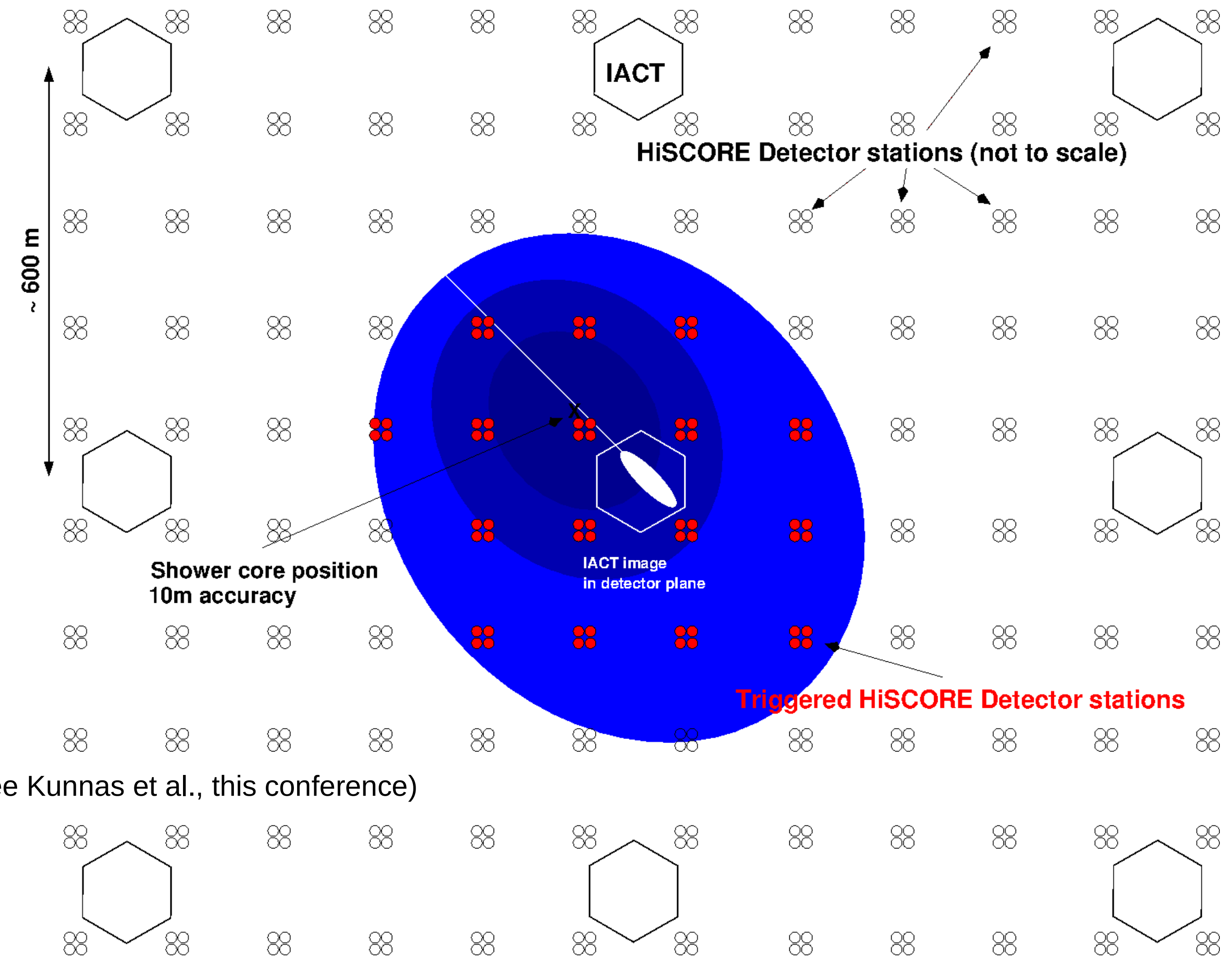
HiSCORE + IACTs



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

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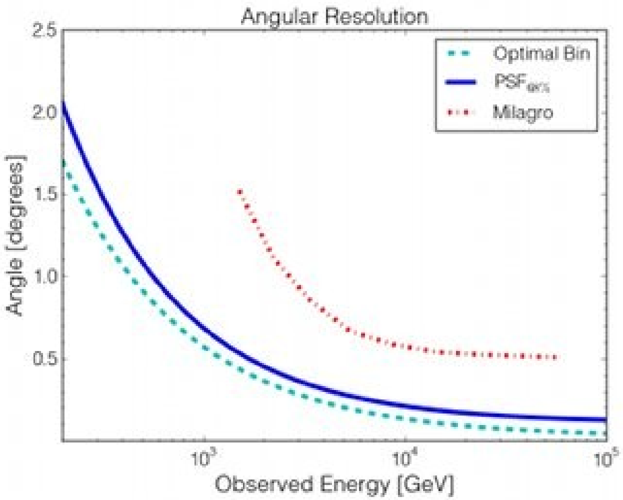
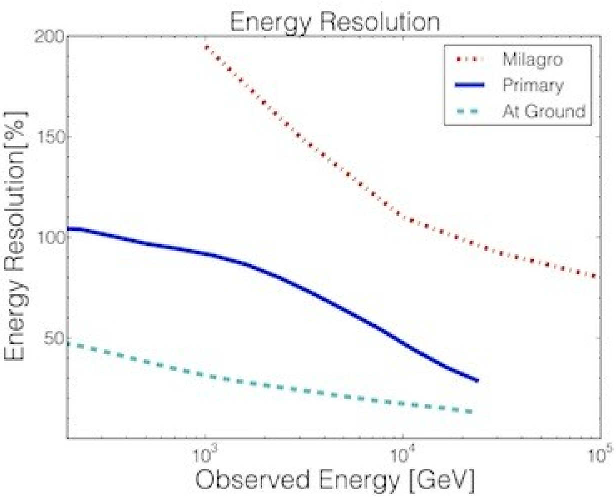
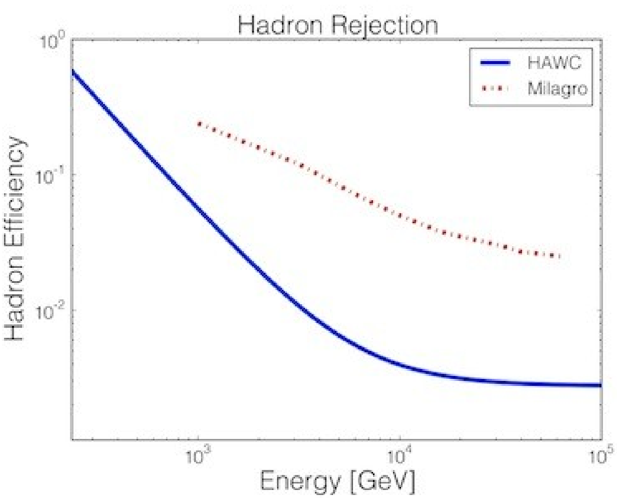
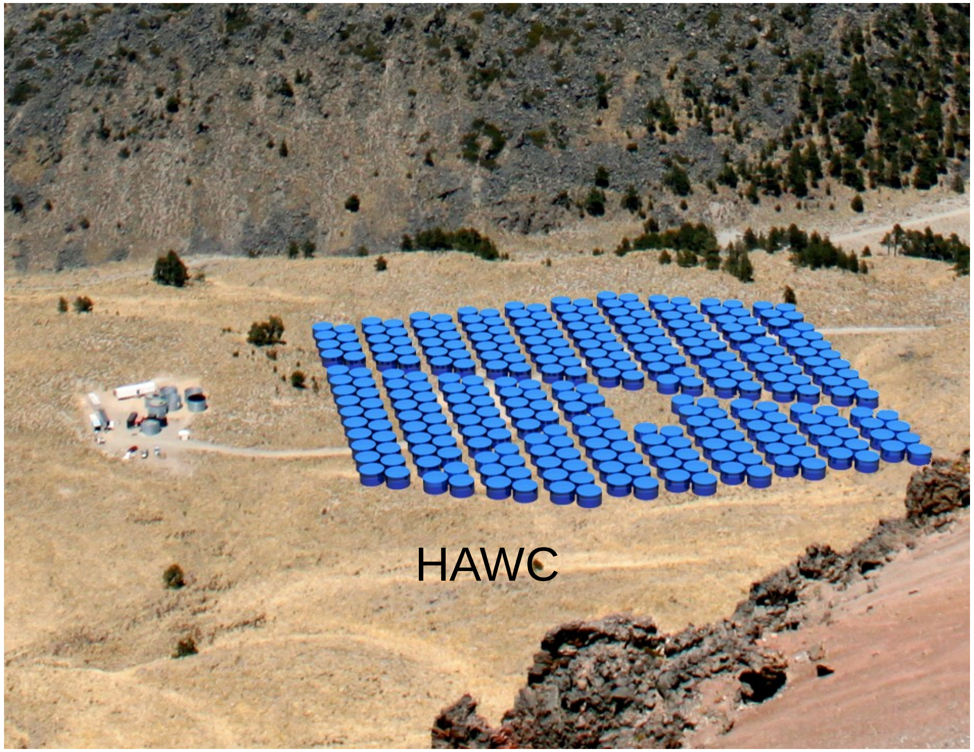
Milagro / HAWC







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



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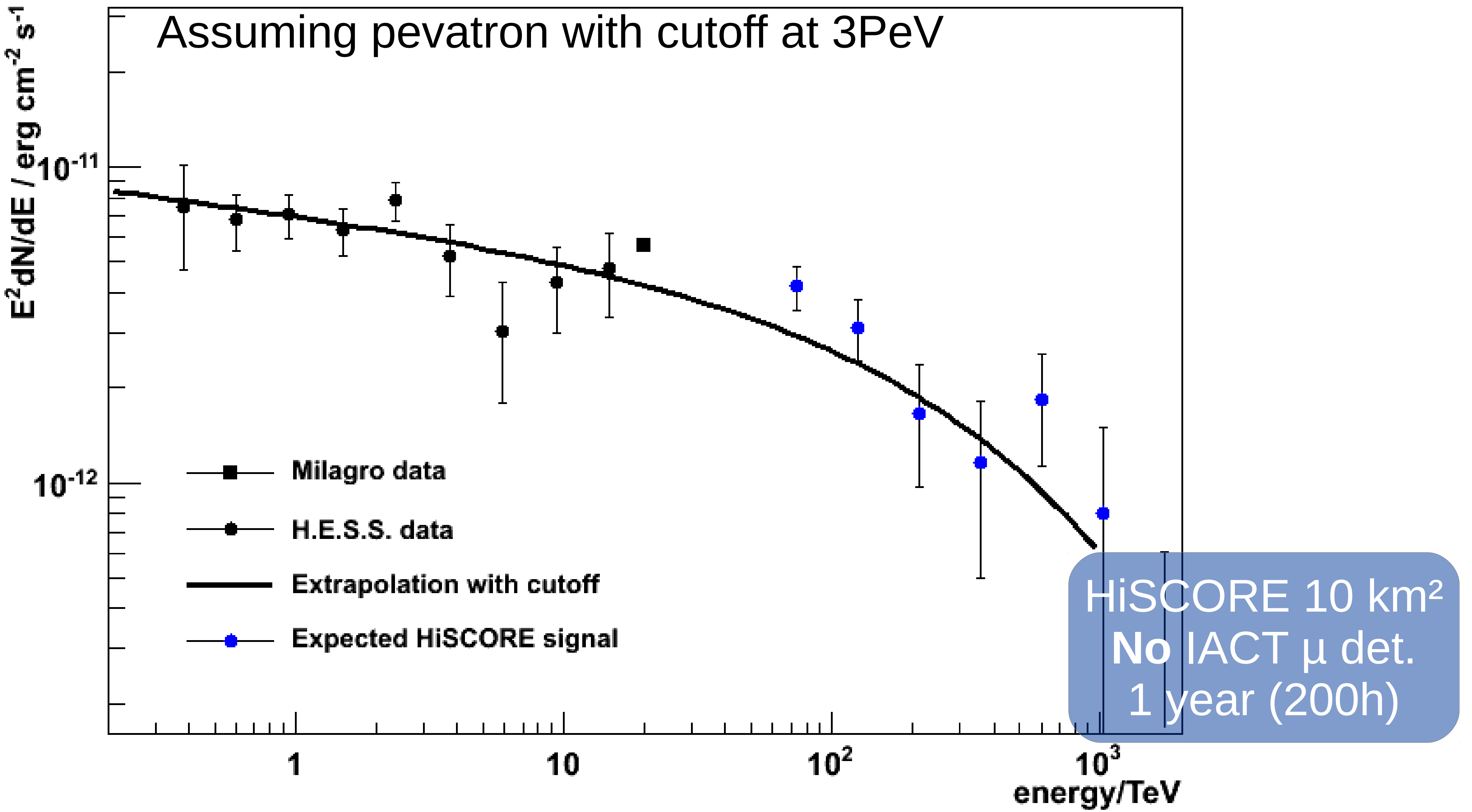
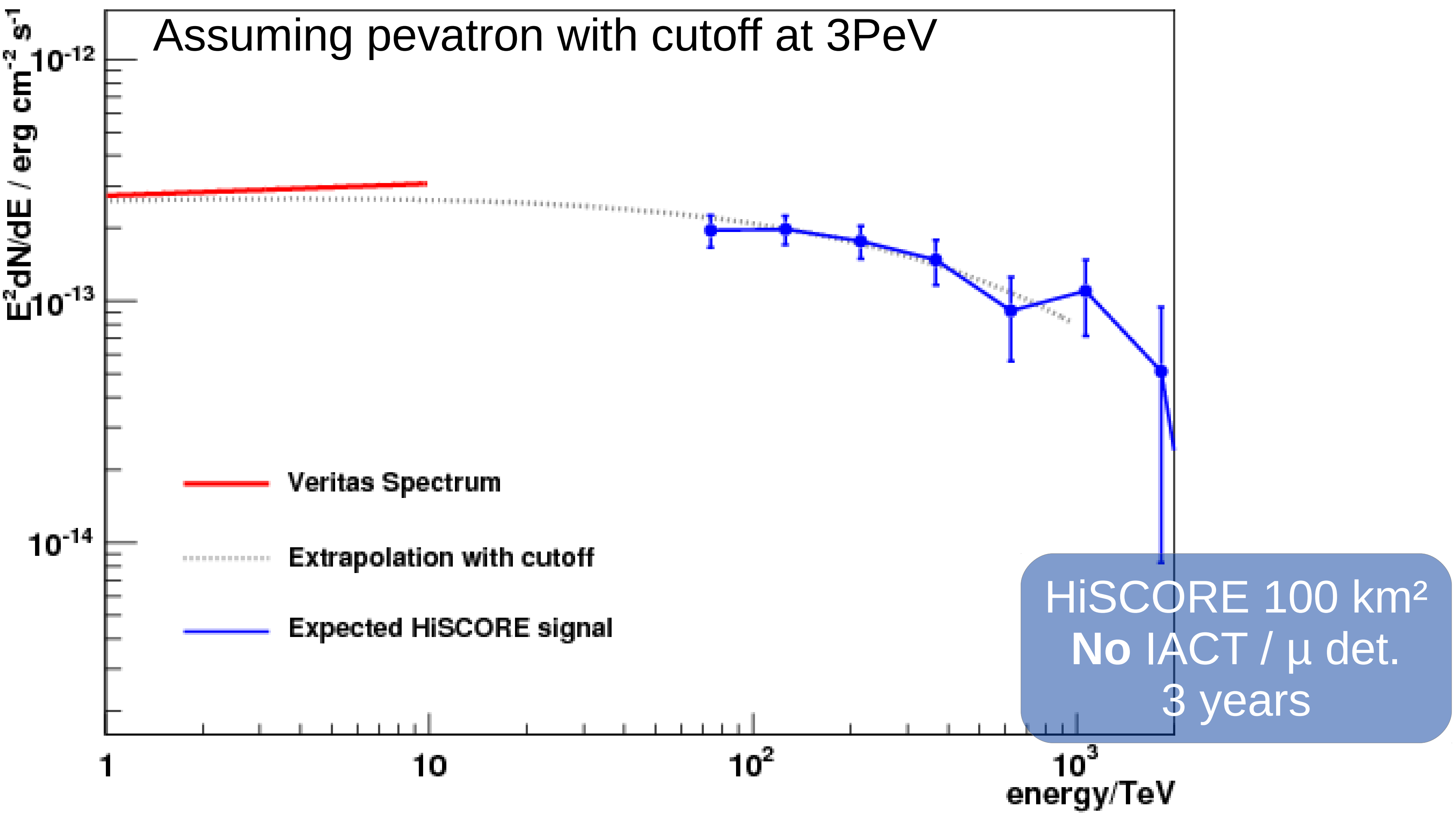


Tycho Supernova remnant



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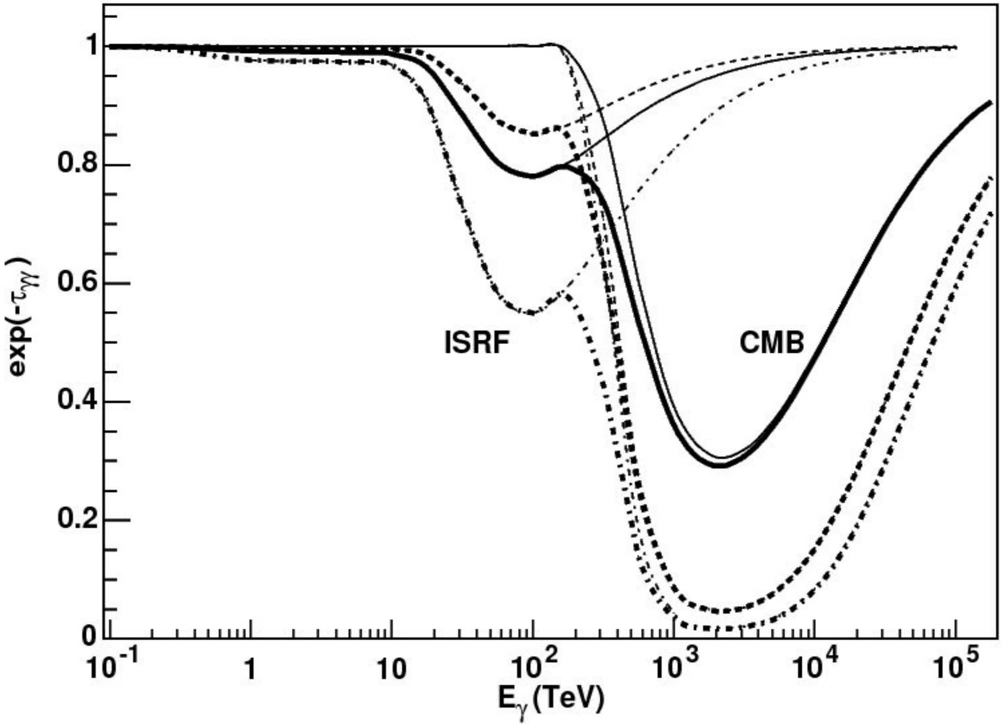
Absorption

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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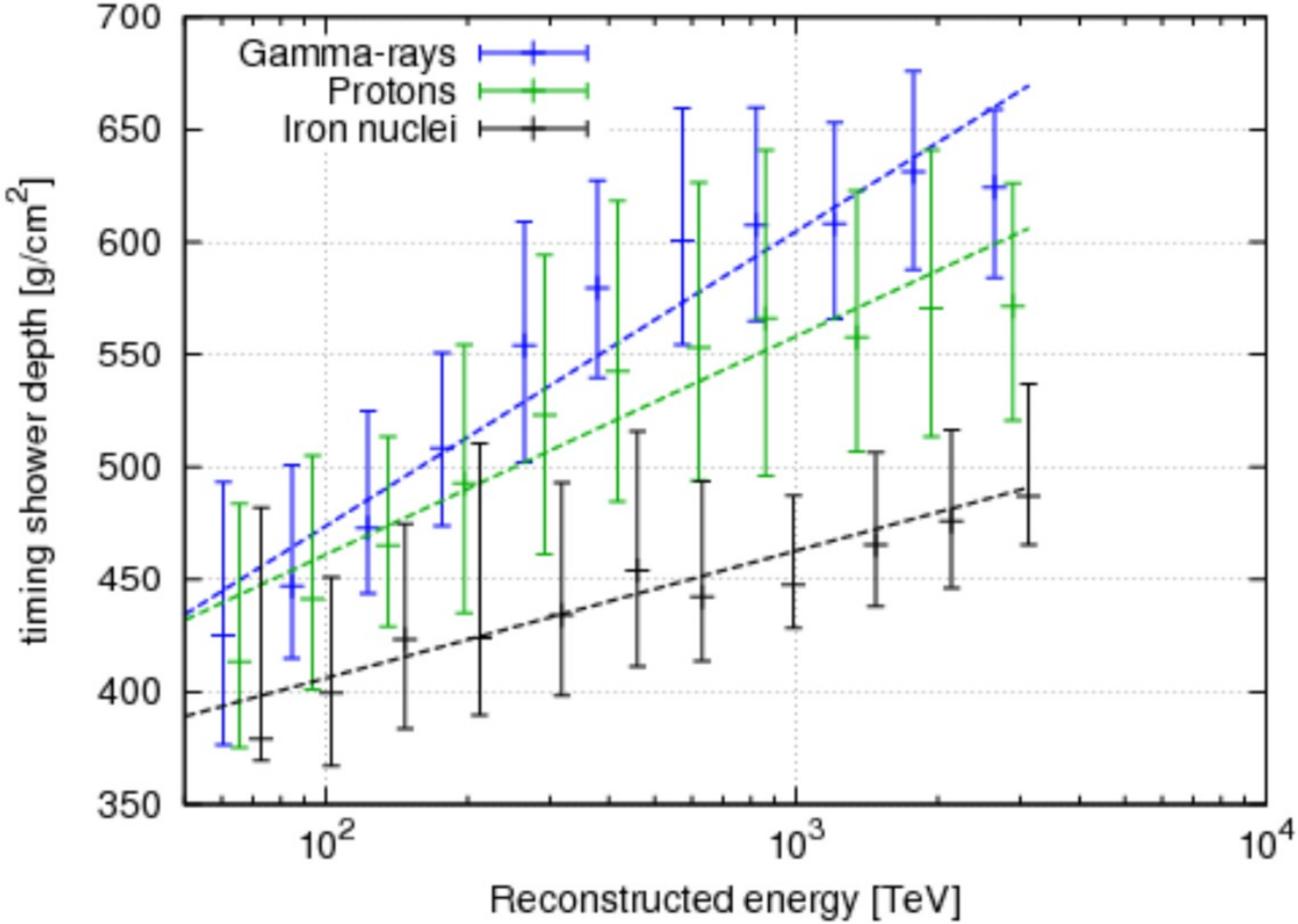
Particle separation Xmax vs. E



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