Multi-TeV to PeV Gamma Ray Astronomy
Motivation and Strategies

Martin Tluczykont

The Future of Research on Cosmic Gamma Rays, La Palma, August 2015
VHE-UHE Gamma-ray astronomy

integral flux / erg cm$^{-2}$ s$^{-1}$

- ▼ KASCADE U.L.
- ♂ H.E.S.S. survey, hard sources
- □ MGRO J1908+06
- ● HESS J1908+06

energy / TeV

September 3, 2014
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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*)

*Galactic objects (Moskalenko 2006)
Absorption ($e^+e^-$), Galactic

Many Galactic sources:
Weak absorption up to 300 TeV

Universal feature:
Distance-dependent absorption above 300 TeV
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

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

Gabici & Aharonian 2007
Key to Multi-TeV—PeV: Large area

1000 hours, 10 γ rays

- 0.1 km²
- 1 km²
- 10 km²
- 100 km²

integral flux / erg cm⁻² s⁻¹ vs. energy/TeV
See Friday: Knödelseder, Chaves, Brown
See Wednesday: Sandoval
See Friday: Simeone
TAIGA

**Integral Flux (erg cm$^{-2}$ s$^{-1}$)**

- $10^{-10}$
- $10^{-11}$
- $10^{-12}$
- $10^{-13}$
- $10^{-14}$

- 1km$^2$
- 10km$^2$

**TAIGA**
# Detection methods for gamma astronomy

<table>
<thead>
<tr>
<th>Method</th>
<th>$E_{\text{thr}}$</th>
<th>Angular resolution</th>
<th>$\Delta E/E$</th>
<th>$y/h$</th>
<th>Duty cycle</th>
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<tbody>
<tr>
<td><strong>Particles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particles</td>
<td>~3 TeV</td>
<td>~1°</td>
<td>20-50%</td>
<td>~1</td>
<td>100%</td>
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<tr>
<td>Water: 100 GeV</td>
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<td>&lt;0.5°</td>
<td>30-50%</td>
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<tr>
<td><strong>Air Cherenkov photons</strong></td>
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From HiSCORE to TAIGA
The HiSCORE Concept

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

- 4x 8inch PMTs
- Winston cones
- Lightcollection 0.5 m²
- GHz readout
- 60° FoV
- “Tilting” for extension of sky coverage
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)
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 accuracies (<0.5 ns)

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

H.E.S.S. Telescopes

Imaging arrays

Timing arrays (=non-imaging)

Past: Themistocle, AIROBICC
Today: HiSCORE, TAIGA
### Air Cherenkov imaging and timing

<table>
<thead>
<tr>
<th></th>
<th>Imaging ACTs</th>
<th>Timing arrays</th>
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</thead>
<tbody>
<tr>
<td><strong>Direction</strong></td>
<td>Image orientation</td>
<td>Shower front arrival times</td>
</tr>
<tr>
<td><strong>Particle type</strong></td>
<td>Image shape</td>
<td>Lateral density function</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arrival times</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time width (FWHM)</td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td>Ch. photon count</td>
<td>Ch. photon count</td>
</tr>
</tbody>
</table>
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
Timing and imaging hybrid detection
Telescope image scaling

Central reconstruction parameter: Shower core position $D_K$

\[ w_{MC} = w_{MC}(\text{size}, D_K, \vartheta) \]

\[ \text{mscw} = \frac{1}{N_{Tel}} \sum_{k=1}^{N_{Tel}} \frac{\text{width}}{w_{MC}} \]
Hybrid imaging + non-imaging

Imaging (stereo)

~100 m

600 m

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Hybrid Image scaling:
$D_K$ from timing array
Image from telescope(s)

$\rightarrow$ large inter-telescope distance $=\text{large } A_{\text{eff}}$
$\rightarrow$ 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 Muon detectors

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

\[
\begin{align*}
\gamma \text{ EAS, } \theta = 40^\circ & \quad E_0 = 3 \times 10^{13} \text{ eV} \\
\gamma \text{ EAS, } \theta = 0^\circ \\
p \text{ EAS, } \theta = 40^\circ \\
p \text{ EAS, } \theta = 0^\circ
\end{align*}
\]

300 TeV proton – 2-6 muons
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

Light guide

Fresnel lens: f/D=1

Photodetectors with light guides

Focused light (with spherical aberrations)

Front-end and control electronics

Readout electronics

Similar detector size

Introducing “Minimal Imaging”

Shayduk et al. 2015, PoS ICRC 2014
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
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: \(~30\text{ns} @ 100 \text{ m}\)
- Cherenkov light front: disk width: <10 ns @ 100 m

![Graph](https://via.placeholder.com/150)
Galactic Gammas beyond 10 TeV

MGRO J1908+06

Tycho (Park et al. 2013)

IC 443

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TAIGA HSCW vs. HESS MRSW

TAIGA

H.E.S.S.

Q-factor $\sim 2$

Q-factor $\sim 3$
Tibet AS-Gamma
Argo YBJ
LHAASO

Tunka-133
Tunka-Rex

HAWC

PACT

STACEE

HAGAR

Tunka-HiSCORE

IceCube
Gamma-ray astronomy

![Graph illustrating gamma-ray astronomy](image)

- Milkyway
- E (eV)
- \( \lambda (\text{Mpc}) \)
- IR/O
- MBR
- Protons

- Curve a
- Curve b
- Curve c

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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

Intensity [p.e.] 0 1912
Peakt ime [ns] -446 526
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

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

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

\[ \delta = \phi + \text{atan2} \left( (x_{Det} - x_{core}), (y_{Det} - y_{core}) \right) \]
Arrival time model

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

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

- **r**: Distance from shower core to detector
- **Slope of atmospheric refractive index**
- **Shower height in km**
- **Zenith angle**
Time calibration

- LED
- St
- Shower front
- HiSCORE detector stations

![Histograms showing data and MC comparison](image)
Energy determination

Energy $\rightarrow$ light density

$Q(x) = \text{LDF at } x \text{ m}$
Energy determination

HiSCORE simulation

![Graph showing energy resolution vs energy for different particles: Iron nuclei (X), Protons (+), Gamma-rays (O).](image)
Shower maximum

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

---

![Graph showing signal width vs. core distance with data points and labels: 'D. Hampf, MT, D. Horns, NIMA 2013'

![Graph showing $X_{\text{max}}$ vs. log FWHM(400) with data points and labels: 'Prosin, ECRS 2010' and 'proton', 'iron']
Shower maximum

HiSCORE Simulation

![Graph showing the depth resolution vs. energy for HiSCORE Simulation with different symbols representing Timing, LDF widths, and combined data.](image)
Particle separation $X_{\text{max}}$ vs. $E$

![Graph showing $X_{\text{max}}$ vs. Energy for different particles (Gamma-rays, Protons, Iron nuclei) with error bars.](image)
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
Particle separation

Lighter particles develop
Higher up in atmosphere
Particle separation (2)

Systematic Xmax difference
Time width and timing model

![Graph](image.png)

- Gamma-rays
- Protons
- Iron nuclei

Number of events vs. Width depth - Timing depth [g/cm²]
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.
Past experiments

- Themistocle
- AIROBICC
## AIROBICC results

**Graph:**

- **Title:** Crab-Nebel
- **X-axis:** Energie [TeV]
- **Y-axis:** Intensity γ-Flux [cm$^{-2}$ s$^{-1}$]

### Table:

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Objekt</th>
<th>$N_{QB}$</th>
<th>$\hat{N}_{QB}$</th>
<th>$N_{OG}$</th>
<th>$S_{DC}$</th>
<th>$S_{burst, exp}$</th>
<th>$S_{var, kol}$</th>
<th>$E_{thr, \gamma}$</th>
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<td>8</td>
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<td>117,4 (1602,5)</td>
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<td>9</td>
<td>AM Her</td>
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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

Telescope [0, 1, 2, 3]
Zenith angle = 41

0.01--0.1 TeV
0.1--1 TeV
1--10 TeV

sim_telarray simulation, 2010
Test width scaling with IACT+HiSCORE “toy-MC-test”

- Full simulation sim_telarray
- 2D-lookup-table for MC-width $w_{MC}(\text{core, size})$
- MC-core \textit{randomized} with HiSCORE resolution
- Use randomized core position for width scaling
Tunka HiSCORE Status

Optical station

Electronic box
Array Optimization HiSCORE

Simulation studies:
→ Large PMTs (12"")
→ Graded array layout
HiSCORE + IACTs
Timing array + imaging telescopes

Central reconstruction parameter: **Shower core position**

- 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 $\times 2-3$

(also see Kunnas et al., this conference)
Milagro / HAWC

http://umdgrb.umd.edu/~bbaugh/work/hawc.php
MGRO J1908+06

Assuming pevatron with cutoff at 3PeV

\[ E^2 \frac{dN}{dE} / \text{erg cm}^{-2} \text{s}^{-1} \]

- Milagro data
- H.E.S.S. data
- Extrapolation with cutoff
- Expected HiSCORE signal

HiSCORE 10 km²
No IACT µ det.
1 year (200h)
Tycho Supernova remnant

Assuming pevatron with cutoff at 3PeV

$E^2 dN/dE / \text{erg cm}^2 \text{s}^{-1}$

Veritas Spectrum
Extrapolation with cutoff
Expected HiSCORE signal

HiSCORE 100 km$^2$
No IACT / $\mu$ det.
3 years

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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)
Particle separation Xmax vs. E

![Graph showing the relationship between reconstructed energy and timing shower depth for different particle types: Gamma-rays, Protons, and Iron nuclei.](image)