TeV gamma-ray astrophysics: today and tomorrow

German Hermann, MPI für Kernphysik
Part I: Observations with the High Energy Stereoscopic System

- Introduction
- The H.E.S.S. experiment
- H.E.S.S. observations
  - Galactic sources
  - Extragalactic physics
  - Quantum Gravity
  - Dark Matter search
- A glance on H.E.S.S. phase 2
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The Cosmic Ray Puzzle

- Mostly nuclei $p$, He, ... Fe
- Also $e^\pm$
- Few $\gamma$, $\nu$
- Non thermal spectrum $dN/dE \sim E^{-\alpha}$
- Isotropic distribution

Discovery in 1912, but
- Cosmic ray origin ?
- Sources ?
- Processes ?

Fluxes of Cosmic Rays

S. Swordy

10 GeV

100 GeV

100 TeV

Galactic

Extra-galactic

Flux (m$^2$ sr s GeV$^{-1}$)

10$^{-30}$

10$^{-28}$

10$^{-26}$

10$^{-24}$

10$^{-22}$

10$^{-20}$

10$^{-18}$

10$^{-16}$

10$^{-14}$

10$^{-12}$

10$^{-10}$

10$^{-8}$

10$^{-6}$

10$^{-4}$

10$^{-2}$

10$^0$

Energy (eV)

$10^13$

$10^{15}$

$10^{17}$

$10^{19}$

$10^{21}$
Potential Sources and Processes

- Super Nova Remnants (SNR)
- Active Galactic Nuclei (AGN)
- Binary Systems
- Pulsar Nebula
- Dark Matter

- SNR as sources of CR
- Acceleration of relativistic particles
- Energy transfer in pulsars
- Environment of neutron stars and Black Holes
- Properties of relativistic jets
- Indirect search for DM
- Cosmology: diffuse EBL GRBs and GRBRs
Tracers to Cosmic Ray Accelerators

Source of Cosmic Rays

\[ p + p \rightarrow \pi^0 + X + \ldots + \pi^\pm \]

\[ \Rightarrow \gamma + \gamma \quad \Rightarrow V_\mu + V_e + \ldots \]

Interstellar magnetic field : \( B \sim 3 \mu G \)

Curvature radius at 1 TeV : \( r \sim 0.3 \times 10^{-3} \) pc
Tracers to Cosmic Ray Accelerators

Source of Cosmic Rays

\[ p + p \rightarrow \pi^0 + X + \ldots \]
\[ \rightarrow \gamma + \gamma \]

Infer properties of primary particle distribution in the sources and their interactions

Observables
- Energy Spectra
  - flux, range, shape
- Source Morphology
- Variability/Periodicity
- Multi-Wavelength (radio, IR, optical, X-ray)
Detection of VHE $\gamma$-rays using Imaging Telescopes

- Image Axis
- Shower Direction
- Intensity
  - Primary Energy
- Image Shape
  - Type of Particle

$\gamma$-Ray (100 GeV)

10 km

5 nsec

$\sim$ 120 m
Detection of TeV γ-rays using Imaging Telescopes

- Angular resolution
- Energy resolution
- Background rejection
- Sensitivity

Stereoscopy:
High Energy Stereoscopic System

Full Operation since January 2004

H.E.S.S. @ Farm Goellschau
Khomass Highlands
1800 m asl
Namibia

© Philippe Plailly
The Telescopes

Alt-Azm mount
107 m² mirror area
380 mirrors each
15 m focal length
Rigid mount

5 deg FoV
960 Pixels / PMTs
Fast Trigger [nsec]
GHz sampling, 16 nsec Int.
Field of View on the Sky

→ Sky Surveys
→ Extended sources
→ Serendipitous discoveries
→ High energy performance

50 % acceptance : 3 deg
20 % acceptance : >4 deg
High Energy Stereoscopic System

Telescopes coupled on hardware level ("central trigger")
Stereo Performance Parameters

State of the Art

Energy threshold: 100 GeV
Energy resolution: 15 %
Field of view: ~ 4 deg
Angular resolution: 0.05° - 0.1°
Pointing accuracy: ~ 10 arcsec
Signal Rate: ~55 / min (Crab-like)
Sensitivity: 1 Crab in 30 sec
0.01 Crab in < 25 h
The sky in TeV gamma rays

2007

2009: > 80 sources
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Significance of $\gamma$-ray excess

~6°

+65°

Galactic Centre

40++ sources, scale saturated at 20 $\sigma$
Classes of Galactic Sources

- Stellar winds
- Supernova remnants
- Pulsar wind nebulae
- Binary Systems
- Molecular Clouds
- Galactic center
- "Dark sources"
Classes of Galactic Sources

- Supernova remnants
- Molecular Clouds
- “Dark sources”
SNRs as Sources of Galactic Cosmic Rays

ASCA SN 1006 data:
“first strong observational evidence that very-high-energy cosmic rays are produced in SNR shocks”

(Koyama, Nature 1995)
TeV Gamma-Rays from (young) SNRs


Particle acceleration to beyond 100 TeV

cut-off power law
\[ \Gamma = 2.04 \pm 0.04 \]
\[ E_c = 17.9 \pm 3.3 \text{ TeV} \]

Proof of TeV emission from the shell of SNRs
What particles are accelerated ... ?

Source of Cosmic Rays

Infer properties of *primary particle distribution* in the sources and their interactions

Observables
- Energy Spectra
  - flux, range, shape
- Source Morphology
- Variability/Periodicity

+ Multi-Wavelength (radio, IR, optical, X-ray)
What particles are accelerated ... ?

Source of Cosmic Rays

\[ p + p \rightarrow \pi^0 + X + \ldots \]
\[ \rightarrow \gamma + \gamma \]

\[ \ldots \text{ protons?} \]

Infer properties of \textit{primary particle distribution} in the sources and their interactions

**Observables**

- Energy Spectra
  - flux, range, shape
- Source Morphology
- Variability/Periodicity

+ Multi-Wavelength (radio, IR, optical, X-ray)

What particles are accelerated ... ?

... protons?
What particles are accelerated?

Source of Cosmic Rays

Infer properties of primary particle distribution in the sources and their interactions

Observables

- Energy Spectra
  - flux, range, shape
- Source Morphology
- Variability/Periodicity
+ Multi-Wavelength (radio, IR, optical, X-ray)

... electrons?
Assume Electrons: Synchrotron + Inverse Compton

\[ P_{\text{Sy}} \propto k \gamma^2 B^2 \]

\[ P_{\text{IC}} / P_{\text{Sy}} \propto 1 / B^2 \]

\[ P_{\text{IC}} \propto k \gamma^2 U_{\text{rad}} \]
Assume Electrons: Synchrotron + Inverse Compton

\[ P_{\text{Sy}} \propto k \gamma^2 B^2 \]

\[ P_{\text{IC}} / P_{\text{Sy}} \propto \frac{1}{B^2} \]


Berezkho, Völk (2006)
Hadronic emission model for RXJ 1713

Collision of protons w/ ambient gas: \( p + p \rightarrow \pi^0 + X \)

Hadronic models describe data reasonably well!
Are SNRs the sources of Galactic cosmic rays??
Towards population studies of shell-type TeV SNRs ...
... and of TeV - SNR associations

- Large FoV
- Deep exposure @ RX J1713.7

→ CTB 37 A and CTB 37B both candidates for the support of hadronic scenario for TeV-γ-ray production H.E.S.S. (2008)
When cosmic rays meet targets ...

Which fraction of SNR energy goes into cosmic-ray nuclei?

How/when are particles released?

Interacting SNR probe
Nature of accelerated particles, particle release, and particle propagation in our galaxy

W28: ~35-150 kyrs old
Molec. clouds ~0.5 – 1 $10^5$ M$_\odot$
SNR interacting with molecular clouds

Which fraction of SNR energy goes into cosmic-ray nuclei?

How/when are particles Released?

If hadronic emission and association w/ clouds ok:
→ x 10-30 higher CR density than in solar system

TeV-Emission from molecular clouds

Interaction of CR with molecular clouds:
→ Future: tracing of CR density in the Galaxy

Aharonian (H.E.S.S.), Nature (2006)

Aharonian (H.E.S.S.), A&A (2008)
Classes of Galactic Sources

- Stellar winds
- Supernova remnants
- Pulsar wind nebulae
- Binary Systems
- Molecular Clouds
- Galactic center

“Dark sources”
Discovery Potential: “Dark Sources”

A bias free view on the sky: ➞ new class of TeV sources
A bias free view on the sky:  \(\rightarrow\) new class of TeV sources

No counterparts in other energy bands seen
(radio, IR, optical, X-ray, …)

Aligned with Galactic plane
All are extended: \(O\ (10\ \text{arcmin})\)
Hard spectrum: \(\Gamma \sim 2.1 \ldots 2.5\)

\(\rightarrow\) Maximum energy output of these sources in TeV \(\gamma\)-rays
\(\rightarrow\) Hadron accelerator ?
\(\rightarrow\) Old PWN ?
\(\rightarrow\) GRB remnant ?
\(\rightarrow\) Dark Matter ?
Discovery Potential: “Dark Sources”

A bias free view on the sky: → new class of TeV sources

No counterparts in other energy bands seen (radio, IR, optical, X-ray, …)

→ More sensitive X-ray and radio observations following the TeV detection
Pulsar discovery triggered by H.E.S.S.

Discovery of PSR J1838−0655
Gotthelf & Halpern (2008) period 70.5 ms, spin-down energy loss $\sim 5.5 \times 10^{36}$ ergs/s

HESS J1837:
7 ' x 3 ' extension
Flux $\sim 0.13$ Crab

2 % of $dE/dt$ of Pulsar needed to power TeV flux!
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Detection of 12 AGN
Discovery of 9 AGN
Upper Limits on >20 Objects (< 0.01 ... 0.05 Crab)

<table>
<thead>
<tr>
<th>Object</th>
<th>Z</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cen A</td>
<td>0.001</td>
<td>AGN (FR I)</td>
</tr>
<tr>
<td>M87</td>
<td>0.004</td>
<td>AGN (FR I)</td>
</tr>
<tr>
<td>Mkn 421</td>
<td>0.030</td>
<td>BLLac (HBL)</td>
</tr>
<tr>
<td>PKS 0548-322</td>
<td>0.069</td>
<td>BLLac (HBL)</td>
</tr>
<tr>
<td>PKS 2005-489</td>
<td>0.071</td>
<td>BLLac (HBL)</td>
</tr>
<tr>
<td>RGB J0152+017</td>
<td>0.08</td>
<td>BLLac (HBL)</td>
</tr>
<tr>
<td>PKS 2155-304</td>
<td>0.116</td>
<td>BLLac (HBL)</td>
</tr>
<tr>
<td>1ES0229+200</td>
<td>0.139</td>
<td>BLLac (HBL)</td>
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<tr>
<td>H2356-309</td>
<td>0.165</td>
<td>BLLac (HBL)</td>
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<tr>
<td>1ES 1101-232</td>
<td>0.186</td>
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</tr>
<tr>
<td>1ES 0347-121</td>
<td>0.188</td>
<td>BLLac (HBL)</td>
</tr>
<tr>
<td>PG 1553+113</td>
<td>&gt;0.25</td>
<td>BLLac (HBL)</td>
</tr>
</tbody>
</table>
The Extragalactic Background Light

EBL contains information on history of star- and galaxy formation

→ Direct measurement very difficult due to foreground light
EBL contains information on history of star- and galaxy formation

- Direct measurement very difficult due to foreground light
Absorption through pair production with diffuse EBL in FIR to UV (for TeV to GeV)
Absorption through pair production with diffuse EBL in FIR to UV (for TeV to GeV)
Reconstructing the EBL density
Assume minimum power law index $\Gamma = 1.5$ at source

“Adjust” EBL such, that observed spectrum compatible with assumed source spectrum

→ EBL intensity
The Extragalactic Background Light

- EBL is at **lower limit**, as obtained from Hubble galaxy count

- Confirmed by **1ES0347**, z = 0.188

- Additional constraints on Mid-IR by **1ES 0229** w/ hard spectrum:
  \[ \text{EBL (2-10 } \mu \text{m)} \sim \lambda^{-1} \]
The Extragalactic Background Light

- EBL is at lower limit, as obtained from Hubble galaxy count
- No significant contribution of pop III stars (z ~ 7...15)
- The Universe is more transparent to Gamma-Rays than expected
- We can “see” further than expected, more sources accessible
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PKS 2155 Monitoring

- Source monitored since 2002 (~240 h)
- Average flux: 3.95 ± 0.39 \(10^{-11}\) cm\(^{-2}\) s\(^{-1}\)
- Huge outburst in July 2006 - two main flares of 28 and 30 July
PKS2155: July 28, 2006

Peak flux ~15 x Crab
~50 x average
Luminosity ~$10^{12}$ x Crab

Variability on timescales 2-3 minutes

\[ R_{BH}/c \sim 1\ldots2 \cdot 10^4 \text{ s} \]

\[ \Gamma \sim 100 \]

“Photons from hotter hell” (T.Weekes)
Probing Quantum Gravity: $c(E) \neq c(E')$?

Postulate:

“…that light is always propagated in empty space with a definite velocity $c$ which is independent of the state of motion of the emitting body”

A. Einstein (1905)
Probing Quantum Gravity: \( c(E) \neq c(E') \)?

Postulate:

“…that light is always propagated in empty space with a definite velocity \( c \) which is independent of the state of motion of the emitting body”

A. Einstein (1905)
Probing Quantum Gravity: \( c(E) \neq c(E') \) ?

\[
c' = c \left( 1 \pm \frac{E}{k \cdot M_P} \pm \frac{E^2}{p^2 \cdot M_P^2} \right)
\]

\[
\Delta t_{QG} = L \left( \frac{1}{c_1} - \frac{1}{c_2} \right) \approx \frac{\Delta E \cdot L}{k \cdot M_P \cdot c}
\]

→ Look a distant objects (O(100) Mpc)
→ Look at real high energies (TeV)

→ Be aware of astrophysical source effects (spectral changes)

\[
M_P = 1.22 \cdot 10^{19} \text{GeV}
\]
Probing Quantum Gravity: $c(E) \neq c(E')$?

(oversampled) light curves in 2 energy bands

$\rightarrow$ Look at modified cross correlation function (MCCF)
Probing Quantum Gravity: $c(E) \neq c(E')$?

Modified cross correlation function

MCCF: peak at 20 sec, but ....

MCCF peak distribution (MC)

... MCCF peak distribution shows that delay is consistent with zero !!!
Probing Quantum Gravity: $c(E) \neq c(E')$?

Most constraining limit on speed of light modification to date:

$$E_{QG} > 5\% \, M_P$$

No trend with redshift observed

HESS, PRL 101 (2008)
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Near Future: H.E.S.S. Phase II

Improved sensitivity (x1.5 - 2) in current regime up to ~ 1 TeV

Energy range down to ~50 GeV will finally become accessible
Near Future: H.E.S.S. Phase II
Near Future: H.E.S.S. Phase II
Last fall in Annecy ...

H.E.S.S. collaboration in front of camera mechanics test setup (09/2008)
Part I: Conclusions from H.E.S.S. observations

From source hunting to real astrophysics ....

- Many discoveries, population studies now possible
- ‘Precision’ measurements
- Cosmology and particle physics
- Composition (e^±, Fe)
- Still more in the pipeline

The path towards CTA is paved
Part II: Design Study for the Cherenkov Telescope Array (CTA)

- The CTA Observatory
- Design Study for CTA
- Technical Developments
- Outlook
Science Potential

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Horan & Weekes 2003

- Current instruments have passed the critical sensitivity threshold and reveal a rich panorama, but this is clearly only the tip of the iceberg.
- Many objects & object classes just below sensitivity limit
- Broad and diverse program ahead, combining guaranteed astrophysics with significant discovery potential
Next Generation: Wish list

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GLAST
MAGIC
H.E.S.S.

$E \times F(>E)$ [TeV/cm$^2$s]

$E$ [GeV]

Crab
10% Crab
1% Crab

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

$10^5$ $10^4$ $10^3$ $10^2$ $10$
Next Generation: Wish list

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GLAST
MAGIC
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Crab

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Next Generation: Wish list
An advanced Facility for ground-based gamma-ray Astronomy

- Improved angular resolution
- Source morphology
- Large FoV (6-8 deg)
- Extended sources, surveys
- High detection rate (large area)
- Transient sources

Population studies extended sources
Precision measurement

Hi-z AGN and pulsars

Exploring the cutoff regime of cosmic accelerators

GLAST
MAGIC
H.E.S.S.

\[ E \times F(>E) \ [\text{TeV/cm}^2 \text{s}] \]

\[ E \ [\text{GeV}] \]

1% Crab

Next Generation: Wish list

Improved angular resolution
Source morphology
Large FoV (6-8 deg)
Extended sources, surveys
High detection rate (large area)
Transient sources

Population studies extended sources
Precision measurement
Goals for CTA
An advanced Facility for ground-based gamma-ray Astronomy

- provide a next-generation instrument for the user community, to address a wide range of topics in high-energy astrophysics and to explore the full sky
- CTA will allow population studies of TeV sources
- New quality of data: in depth studies on individual objects
- expected large number of detectable objects – O(1000) – implies operation as open observatory, with appropriate tools for data dissemination and data analysis
- expect (500+) users from astronomy, astroparticle physics, plasma physics, particle physics (DM), cosmology
The CTA Observatory

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One observatory with two site operated by one consortium

Northern Array (50 ME)
- complementary to SA for full sky coverage
- Energy range:
  - some 10 GeV …. ~1 TeV
- Small field of view
  - Mainly extragal. Sources

Southern Array (100 ME)
- Full energy and sensitivity coverage
  - some 10 GeV … 100 TeV
- Angular resolution:
  - 0.02 … 0.2 deg
- Large field of view
  - Galactic + Extragal. Sources
How to get there?

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![Graph showing E vs. E*F(>E) for GLAST, MAGIC, and H.E.S.S. with蟹 and 10%蟹, 1%蟹 annotations.](image)
Core array:
many ~12 m telescopes
medium FoV (6-8 deg)

Low-energy section
a few 24 m telescopes
~ 4-5 deg FoV

High-energy section
~ 6 m diameter
large FoV (8-10 deg)

Possible Implementation
Do we know, how to build telescopes?

yes !!!

but ...

HESS I

MAGIC

telescopes to scale

HESS II

under construction
• **Current telescopes not optimized for large-scale production**
  - Cost would exceed target cost (100 M€ for full site) by factor 1.5 to 2
  - Instrument reliability needs to be improved / built-in

• **We believe we can built even better / more efficient telescopes**
  - wider field of view
  - improved photo sensors
  - improved electronics signal recording
  - overall optimized array layout

• **Need to develop tools to operate a user facility** and to provide effective data access
  - Observation scheduling and system control
  - Science data center and data access tools
... and there are ‘a few’ challenges

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Will need

- O(50-100) telescopes, core array
- O(10000) m² mirror area
- O(70) m² photo sensitive area
- O(100k) electronics channels

→ Factor of 10 in sensitivity with only factor of 10 in M€

Find an optimized array layout that has the required performance

Optimize design for effective production / commissioning, and for stability and high reliability
... and there are ‘a few’ challenges

An advanced Facility for ground-based gamma-ray Astronomy

Will need
O(50-100) telescopes, core array
O(10000) m² mirror area
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→ Factor of 10 in sensitivity
  with only factor of 10 in M€

Find an optimized array layout
that has the required performance

Optimize design for effective production /
commissioning, and for
stability and high reliability

→ Design Study
CTA involves scientists from
Czech Republic
Germany
Finland
France
Italy
Ireland
Japan
UK
Poland
Spain
Switzerland
Sweden
Armenia
South Africa
Namibia

and from several communities
astronomy & astrophysics
particle physics
nuclear physics

about 250-300 scientists working
currently in the field will be
directly involved,
user community significantly larger

Design Study in a joint effort!
Will need
O(50-100) telescopes, core array
O(10000) m² mirror area
O(70) m² photo sensitive area
O(100k) electronics channels

→ Factor of 10 in sensitivity
with only factor of 10 in M€

Find an optimized array layout
that has the required performance

Optimize design for effective production / commissioning, and for
stability and high reliability
A complex optimization problem

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Overall optimization under given cost constraints
Camera: what Pixel Size is really needed?

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0.07°
HESS II

0.10°

0.14°
HESS I

0.20°
HEGRA

0.28°

Legend:
+ pixel above threshold
- pixel in image
x marginal/isolated signal
* simulated direction
O reconstructed direction
second moments
ellipse (*1/2)

0 6 15 30 60 150 300 p.e.
Example: Sensitivity vs Pixel Size

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Factor 16 in no of pixels & camera cost

→ 0.14 ... 0.2 deg
pixel size reasonable
MC: Large Scale End-2-End Simulations

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Large scale simulation of “Hyper-Array” with 275 telescopes of 5 different types, sizes, ...

→ Selection of candidate arrays under cost constraints
→ Study of performance
→ Assessment of physics performance

~ 0.5 Billion events generated during last few months
Preliminary MC Results: it’s feasible!

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From K. Bernloehr (not fully optimized, yet)

Energy [TeV]

Integral flux limit [1/(s cm²)]

0.1% Crab

50 h
5 σ
10 events

GLAST (1 yr)
GLAST (5 yrs)
MAGIC
MAGIC II stereo
VERITAS
H.E.S.S.
Camera: Electronics and Photon Detectors

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- Acquisition
- Readout
- Trigger
- Mechanics
- Light concentrator and Photon detector

< ~400 Euro per channel

from P. Vincent
Cameras: large Quantity of Components

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O (100 000 ) channels
photomultipliers, pre-amps
light concentrators
high voltage, ...

Smart & cost effective design needed
(±10 E/channel ⇒ ± ~1 Telescope)

Current cameras: O(1000 € / chan) …
Improved PMTs

Cooperation with manufacturers to improve/adapt performance to CTA specific requirements → e.g. low afterpulsing, hi QE, cost, cost, cost …

Baseline Design:
→ PMTs

Keeping an eye on future developments e.g. HPDs (still way too expensive)
Photon Detectors: PMTs Baseline Design

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Improved PMTs

Cooperation with manufacturers to improve/adapt performance to CTA specific requirements → e.g. low afterpulsing, hi QE cost, cost, cost ….

Silicon PMTs

- Under development in many labs and in industry
- Still a significant step to a large-area detector
- Cost and practical performance open
- Particularly interesting for low-energy section
- R&D path for possible upgrades
Camera Readout Options
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Existing pipeline chips: e.g. SAM (H.E.S.S. 2), DRS4 (MAGIC 2)
GHz sampling;
11-12 bit dynamic range
256 - 1024 cells depth

1) Existing solutions
  Proven to work
  → Need to be adapted &
  integrated w/ RO-scheme
  → cost optimization
  low risk

2) NeCTAr project (2009-2011)
  highly integrated FE chip
  → Cost reduction

Hz sampling;
11-12 bit dynamic range
256 - 1024 cells depth

GHz sampling
Proven to work
→ Need to be adapted & integrated w/ RO-scheme
→ cost optimization
low risk

O(nsec) Cherenkov flashes
→ O(100 MHz - GHz) sampling

few nsec
1 Byte / pixel / evt  
(20 nsec @ ~ 800 MHz x 2 gain)  
2000 channels  
10 kHz camera triggers  
→ ca. 600 MByte/sec  

For optimum use of pulse shape, data needs to be analyzed by using info from all Pixels / correlations and not just per pixel

→ Bus – System into CPU ?
Ethernet-based front-end readout: tests

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FPGA MAC sender:
100 MBit and GBit Eth interface successfully implemented (and used)

switch & server bandwidth:
48 groups (nodes) sending data transferred into one server
→ 700 MByte/sec (loss free)
(low cost solution, using standard commercial components)

3 x 48 Port GB Ethernet Switch
100 x RJ 45 GBit Ethernet

Pixel 1
Analogue pipeline w/ ADC or FADC
Buffer/FPGA

Pixel 16

Pixel 1
Analogue pipeline w/ ADC or FADC
Buffer/FPGA

Pixel 16

Pixel 1

Pixel 16

→ ~ 5MB/sec

PC Server
8 x 1 GB Ethernet

8 x 1 GB Ethernet

German Hermann, MPI für Kernphysik

www.cta-observatory.org
## Tentative Timeline

**An advanced Facility for ground-based gamma-ray Astronomy**

<table>
<thead>
<tr>
<th></th>
<th>06</th>
<th>07</th>
<th>08</th>
<th>09</th>
<th>10</th>
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<td>Array layout</td>
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<tr>
<td>Telescope design</td>
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“Kick-off”: Barcelona, Jan 24-25
TeV gamma-ray astronomy: today and tomorrow

Thank you !!!

German Hermann, MPI für Kernphysik

ICRR, March 17, 2009