Evaluation and Integration of SiPMs in Air-Shower Imaging Telescopes for the Detection of Ultrahigh Energy Neutrinos
The Era of Multi-Messenger Astrophysics

- Isotropic γ-ray background
- High-energy neutrinos (flavor-average)
- Ultra-high energy cosmic rays
- Proton ($E^{-2}$)
- Cosmogenic neutrinos ($\nu + \bar{\nu}$)

- Energy $E$ [GeV]
- $E^2 \phi$ [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$]

- γ-rays from $\pi^0$ decay
- $\nu_\mu + \bar{\nu}_\mu$
Air-Shower Imaging

Proven Technique
- Angular resolution $\sim 0.1^\circ$
- Energy resolution $\sim 10\%$
- Excellent background suppression

Nepomuk Otte
Trinity: Baseline Configuration

- 2 km above ground
- 10 m² effective mirror area
- 3° FoV above horizon, 2° FoV below horizon
- 360° azimuthal acceptance
- 0.3° minimal reconstructable image length

Details in Otte PRD (2019) arXiv 1811.09287
Air Showers for Lovers
Detected Cherenkov Light

- Calculated with PDE of Hamamatsu S14520
- 50 pe threshold for 10m² mirror and 10⁸ GeV tau

Graph showing the photo-electron density [pe m⁻² GeV⁻¹] as a function of angle α [degrees] for distances of 25 km and 195 km, indicating lower counts at higher angles.
Spread of Photon Arrival Times

![Graph showing the spread of photon arrival times with time spread in ns on the y-axis and offset angle in azimuth in degrees on the x-axis. The graph includes data for different fractions of photons at centers 25%, 50%, 75%, and 90%.]
1° veto region

4° signal region
Optics

Based on J. Cortina et al., Astrop. Physics 72 (2016) 46

- **FoV 5° X 60°.**
- 5.6 m focal length.
- 0.3° optical PSF.
- 20 mm Winston cones coupled to **9 mm SiPMs.**
- 3,300 pixel camera.
- 68 m² mirror area → **16 m²** in any direction.
- Rotates in elevation.
- Thin-glass replica mirror technology ~$2k/m².
- Implementation based on MAGIC structure.
- $170k for one telescope (excl. camera).
Photon Detector Requirements

- High sensitivity >600nm where Cherenkov emission peaks
- Single photoelectron signals < 100 ns
- Sensor diameter <1 cm
- A dark-count rate of several 100 kHz is below the background photon intensity

**SiPMs are a good match**
Evaluated SiPMs

- FBK RGB-HD with 15um and 25 um pixels
- FBK NUV-HD (used in CTA-SCT camera upgrade)
- Hamamatsu S14520 50 um cells (Optimized for CTA, p-on-n)
- Hamamatsu S14420 50 um cells (Optimized in red, n-on-p)

Procedures described in NIMA Otte et al. (2016)
Photon Detection Efficiency

@ 90% breakdown probability
Photon Detection Efficiency

@ 90% breakdown probability

S14520

S14420
Figure of Merit Studies for SPB2

Nepomuk Otte
<table>
<thead>
<tr>
<th>Device</th>
<th>Peak PDE [%]</th>
<th>Peak Wave-length [nm]</th>
<th>Optical Cross-talk [%]</th>
<th>After-pulsing [%]</th>
<th>Delayed Optical Crosstalk [%]</th>
<th>Dark-count rate [kHz/mm²] @ 20°C</th>
<th>Operating Voltage [V]</th>
<th>Over-voltage [%]</th>
<th>Cell size [um]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGB-HD</td>
<td>27</td>
<td>560</td>
<td>14</td>
<td>1.5</td>
<td>4</td>
<td>200</td>
<td>33</td>
<td>11</td>
<td>25</td>
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<tr>
<td>NUV-HD</td>
<td>56</td>
<td>390</td>
<td>15</td>
<td>1</td>
<td>&lt;1</td>
<td>80</td>
<td>31</td>
<td>22</td>
<td>40</td>
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<tr>
<td>S14520</td>
<td>52</td>
<td>470</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>50</td>
<td>44</td>
<td>9</td>
<td>50</td>
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<tr>
<td>S14420</td>
<td>46</td>
<td>610</td>
<td>6</td>
<td>&lt;1</td>
<td>0.5</td>
<td>200</td>
<td>50</td>
<td>20</td>
<td>50</td>
</tr>
</tbody>
</table>

See backup slides for details
SPB2

- Ultra-long duration flight from New Zealand in 2021
- One Cherenkov Telescope
- One Fluorescence Telescope

**Objectives**

- Test imaging of air-showers from high altitudes
- Evaluate background sources
Electronics for SPB2 and Trinity
Signal Chain Proof of Concept

For details see arXiv:1907.08728
Front-End Electronics

50 mW/channel
Conclusions

- Air-shower imaging is a viable technique to search for UHE neutrinos from ground and space.
- New experiments feasible because of SiPMs
- Different SiPMs show similar and acceptable performance
- More ASIC developments of front-end electronics for SiPMs would be great.
Figures Measurement Results
Comparison
FBK RGB-HD and
Hamamatsu S14520-6050CN

Nepomuk Otte
School of Physics
&
Center for Relativistic Astrophysics
change in breakdown voltage
24.2±0.7 mV/°C

change in breakdown voltage
37.2±0.4 mV/°C
Hamamatsu S14420-3050WO-RESIN

Nepomuk Otte

School of Physics
&
Center for Relativistic Astrophysics
Specs

- Round device 3mm diameter
- 50um cells
- Estimated number of cells 2827
- Operating point 20% above breakdown
- 40ns boundary between delayed OC and AP
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change in breakdown voltage 48.8±1.0 mV/°C
change in eff. capacitance
-0.149±0.006 ΔfF/°C
rate doubles every $5.5^\circ C$
Measurements: FBK NUV-HD3-4

Katherine Powell
Nepomuk Otte
Specs

- Uncoated
- 6.3mm x 6.3mm
- 40 um cells
change in eff. capacitance
0.008±0.006 ΔfF/°C
The graph shows the change in quench resistance with temperature. The data points are represented by black circles, and the trend line is a red line. The change in quench resistance is given as 

\[ \text{change in quench resistance} = \frac{-3652 \pm 54}{\degree C} \]
Delayed OC

Amplitudes and Times

Afterpulsing

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Other backup
Bias Curves
Triggered Viewing Angles

![Graph showing probability vs. angle α]

- **X-axis (angle α [degrees])**:
  - Range from 0 to 20 degrees
- **Y-axis (probability)**:
  - Range from 0.005 to 0.025 probability

**Top View Diagram**
- **α**: Angle of interest
- **s**: Other relevant angle or parameter
- **ζ**: Additional angle or parameter

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Signal Chain

Same as in NO et al. EUSO-SPB2 PoS(ICRC2019)977

- **MUSIC**: preamp ASIC developed for IACTs.
- **AGET digitizer**: 100MS/s, switch capacitor readout, 12 bit.
- **$100 per channel → $330k per camera**

Tested with picosecond laser flashing Hamamatsu S14520 SiPM + MUSIC + AGET
Acceptance vs. Light Collection Area

![Graph showing acceptance vs. light collection area](image)

- Radial acceptance in cm² s sr
- Distance of tau emergence from telescope in km
- Mirror sizes: 1 m², 5 m², 10 m², 100 m²

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How much Field of View?

Full image containment is required.
UHE Tau initiated Air-Shower Fun Facts

Emergence angle: ~5%

Shower length: ~10 km

Height of shower tip above ground: ~1 km
Sensitivity vs. FoV above Horizon

![Graph showing sensitivity vs. FoV above horizon for different angles (0°, 1°, 2°, 10°). The graph plots energy squared dN/dE (GeV cm² s⁻¹ sr⁻¹) against energy (GeV).]
Sensitivity vs. FoV below Horizon

![Graph showing the sensitivity vs. FoV below horizon with different angles: 0°, 1°, 3°, 10°, and 89°. The y-axis represents $E^2 dN/dE$ in $\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, and the x-axis represents energy in $\text{GeV}$.)]
Acceptance
Impact of Night Sky Background

\( E^2 \frac{dN}{dE} \ [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \)

- **NSB**
  - 1 \times \text{nominal}
  - 2 \times \text{nominal}
  - 10 \times \text{nominal}

Energy [GeV]

- \(10^7\) to \(10^{11}\)
Thin-Glass Mirrors
POEMMA MISSION

Mission Lifetime: 3 years (5 year goal)
Orbits: 525 km, 28.5° Inc
Orbit Period: 95 min
Satellite Separation: ~25 km – 1000+ km
Satellite Position: 1 m (knowledge)
Pointing Resolution: 0.1°
Pointing Knowledge: 0.01°
Slew Rate: 8 min for 90°
Satellite Wet Mass: 3860 kg
Power: 2030 W
Data: 1 GB/day
Data Storage: 7 days
Communication: S-band (X-band if needed)
Clock synch (timing): 10 nsec

Operations:
- Each satellite collects data autonomously
- Coincidences analyzed on the ground
- View the Earth at near-moonless nights, charge in day and telemeter data to ground
- ToO Mode: dedicated com uplink to re-orient satellites if desired
POEMMA: study collaboration

USA: University of Chicago: Angela V. Olinto (PI), R. Diesing
NASA/MSFC: P. Bertone, M. J. Christl, R. M. Young,
University of Alabama, Huntsville: J. Adams, E. Kuznetsov, P. Reardon,
University of Utah: D. R. Bergman
Colorado School of Mines: J. Eser, F. Sarazin, L. Wiencke,
City University of New York, Lehman College: L. Anchordoqu, T. C. Paul, J. F. Soriano
Georgia Institute of Technology: A. N. Otte
Space Sciences Laboratory, University of California, Berkeley: E. Judd
University of Iowa: M. H. Reno

DENMARK: NBI: M. Bustamante


GERMANY: KIT: R. Ulrich, M. Unger; ESO: F. Oikonomou

ITALY: Universita di Torino: M. E. Bertaina, F. Bisconti, F. Fenu, A. Liberatore, K. Shinozaki:
Gran Sasso Science Institute: R. Aloisio, A. L. Cummings, I. De Mitri; INFN Frascati: M. Ricci

JAPAN: RIKEN: M. Casolino, Y. Takizawa

SLOVAKIA: IEP, Slovak Academy of Science: S. Mackovjak

SWITZERLAND: University of Geneva: A. Neronov
POEMMA designed to observe neutrinos with $E > 20$ PeV through Cherenkov signal of tau decays.
POEMMA
Hybrid MM Focal Surface

Cherenkov Detection with SiPMs:
20 nsec sampling

30 SiPM focal surface units
Total 15,360 pixels
512 pixels per FSU (64x4x2)
Si-Diode for LEO radiation backgrounds rejection
Limb for Neutrinos & UHECRs
Radius 2.6-3.7 $10^3$ km

Observing Modes

Nadir for UHECR:
Radius 200-400 km
POEMMA
Neutrino TOO
(Targets of Opportunity)
Venters et al. arXiv: 1906.07209

Transient Events
few to 100 Million neutrinos/event

10 neutrinos up to 120 Mpc!

<table>
<thead>
<tr>
<th>Source Class</th>
<th>No. of $\nu$'s at CC</th>
<th>No. of $\nu$'s at 3 Mpc</th>
<th>Largest Distance for 10 $\nu$'s per event</th>
<th>Model Reference</th>
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<tbody>
<tr>
<td>TDEa</td>
<td>$10^8$</td>
<td>7</td>
<td>2.5 Mpc</td>
<td>Dai &amp; Fang (2017) average</td>
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<tr>
<td>TDEa</td>
<td>$5 \times 10^6$</td>
<td>35</td>
<td>6.5 Mpc</td>
<td>Dai &amp; Fang (2017) bright</td>
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<td>TDEa</td>
<td>$2 \times 10^6$</td>
<td>1668</td>
<td>40 Mpc</td>
<td>Lunardini &amp; Winter (2017)</td>
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<td>$M_{\text{MBH}} = 5 \times 10^9 M_\odot$</td>
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<tr>
<td>TDEa</td>
<td>NA</td>
<td>16000</td>
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<td>Blazar Flares</td>
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<td>1400</td>
<td>35 Mpc</td>
<td>Rodrigues et al. (2018) -</td>
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<td>FSRQ proton-dominated</td>
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<td></td>
<td></td>
<td>advective escape model</td>
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<tr>
<td>BHB-BHB</td>
<td>$6 \times 10^7$</td>
<td>400</td>
<td>20 Mpc</td>
<td>Kotera &amp; Silk (2016)</td>
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<td>$\tau_{\text{dur}} \sim 10^4 \text{s}$</td>
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<td>BHB-BHB</td>
<td>$3 \times 10^{10}$</td>
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<td>400 Mpc</td>
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<td></td>
<td>$\tau_{\text{dur}} \sim 10^5 \text{s}$</td>
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<tr>
<td>NS-NS</td>
<td>$3 \times 10^7$</td>
<td>188</td>
<td>13 Mpc</td>
<td>Fang &amp; Metzger (2017)</td>
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<td>WD-WD</td>
<td>39000</td>
<td>0.3</td>
<td>500 kpc</td>
<td>Xiao et al. (2016)</td>
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<td>Newly-born</td>
<td>8000</td>
<td>0.06</td>
<td>226 kpc</td>
<td>Fang (2015)</td>
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<td>pulsars</td>
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</tbody>
</table>

Binary Coalescence

Tidal Disruption Events
Artists rep TDE (star torn BH). Credit: NASA / CX / M. Weiss

Newborn Pulsars
Crab 965 years ago!

Gamma-Ray Bursts, Blazar Flares
GW170817 follow up with POEMMA
arXiv:1906.07209

Long bursts

Short bursts
Science Motivation:

- What is the composition of UHECR?
- What are the sources of UHECR?
- Extension of IceCube detected $\nu$ flux to $10^9$ GeV?
- Search for “new” physics
Three year sensitivity