IT’S A VIOLENT VHE SKY...

A transit IACT to survey half of the VHE γ-ray sky

J. Cortina, R. López-Coto, A. Moralejo (IFAE Barcelona)
MACHETE: A transit IACT to survey half of the VHE $\gamma$-ray sky

J. Cortina, R. López-Coto, A. Moralejo (IFAE Barcelona)
IACTs are pointing instruments

Fermi sky (2 yr exposure)

The whole sky = 42000 deg$^2$

Field of View (FOV) of a typical IACT (HESS ~20 deg$^2$, CTA-SCT~50 deg$^2$)
Surveys with IACTs

- Say we need 10h to achieve enough sensitivity. We would need 10000 hours to scan the whole sky: telescopes need ~10 years to collect them.
- It is achievable but there are many other ideas to exploit an IACT for 10 years.
- As a result only a survey of the galactic plane has been performed (HESS, about 1000 deg²). Adding all pointing observations, we may have explored ~5% of the sky.
- What is in the other 95% of the sky? Active galaxies, off-plane galactic sources, dark matter clumps? Important to make a Full sky survey in VHE.
- What it’s more, the VHE sky is changing all the time, so we would need to repeat the survey after a few years and we’d very much like to monitor it every night.
E_\gamma < 100 \text{ GeV}: \text{ space based surveys}

**Fermi-LAT**

- Scans full sky every 3h.
- Very small collection area for >100 GeV observations, i.e. limited sensitivity to VHE transients.
- Angular resolution ~0.1° i.e. as good as IACTs.
- No obvious replacement for Fermi-LAT in the future (>2020?)

MACHETE: a transit wide FOV IACT
$E_\gamma > 1$ TeV: surveys with non-IACTs

- $\sim 10$-15x more sensitive than Milagro.
- Angular resolution $\sim 1^\circ$.
- Hadron rejection poorer than IACTs, i.e. worse sensitivity
- Energy range: $> 1$ TeV.
- Larger: HiSCORE in Russia, LHASSO in China, under construction, but targeting higher energies

HAWC
Just started to take data
The archetypal wide FOV telescope: the Schmidt telescope

How to build a Schmidt:
STEP 1. Start with a **spherical mirror**. It has aberrations but only spherical aberrations.
The archetypal wide FOV telescope: the Schmidt telescope

STEP 2. Make the focal plane spherical, with center at center of mirror. All incident directions become equivalent.
The archetypal wide FOV telescope: the Schmidt telescope

STEP 3. For a spherical mirror as rays hit further and further away from optical axis they get more and more defocused.
The archetypal wide FOV telescope: the Schmidt telescope

STEP 3. … adding a “stop” reduces the aberration.
The archetypal wide FOV telescope: the Schmidt telescope

STEP 3. Considering all incident directions: where shall we place the "stop"?
At the mirror’s center of curvature, so that all directions remain equivalent.
The archetypal wide FOV telescope: the Schmidt telescope

STEP 4. Add the Schmidt **corrector plate** at the stop. That eliminates spherical aberrations.
The archetypal wide FOV telescope: the Schmidt telescope

Well, let’s build a “Schmidt IACT”!
This has been proposed: Mirzoyan & Andersen, ApP 31 (2009) 1,
with D=7m mirror, FOV $\varnothing=15^\circ$, $f/D=0.8$, PSF RMS=1 arcmin.

Unfortunately:
- It has chromatic aberration (lens!)
- For the corrector plate they propose a 7m $\varnothing$ PMMA Fresnel lens of 17mm max thickness: challenging and probably expensive.
- Bulky instrument: 3 large elements (mirror, camera and corrector plate).
Deconstruct a Schmidt

4. Add the “world-famous” Schmidt corrector plane at the stop. That eliminates (first order) spherical aberrations.

We live with the aberration: after all IACTs don’t need excellent optics
Deconstruct a Schmidt

STEP 3. As rays hit further and further away from optical axis, they get more and more defocused. Add a "stop".

Implement it placing a “light concentrator” on each of the pixels

This effectively defines $D$. 

MACHETE: a transit wide FOV IACT
No limit to field of view!??

Since there is no physical stop the aperture does not decrease as we go further and further off-axis. So we can go to any off-axis angle…!?
No, there’s a limit

A limit is set by the **shadowing of the camera** on the mirror.

Here is an example: D=12 m, f=17 m \((f/D=1.42)\), circular camera

<table>
<thead>
<tr>
<th>FOV (\phi) (°)</th>
<th>(S_{\text{cam}}) (m(^2))</th>
<th>On-axis shadowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.77</td>
<td>1.6%</td>
</tr>
<tr>
<td>10</td>
<td>7.1</td>
<td>6.3%</td>
</tr>
<tr>
<td>15</td>
<td>16.0</td>
<td>14%</td>
</tr>
<tr>
<td>20</td>
<td>28.4</td>
<td>25%</td>
</tr>
<tr>
<td>25</td>
<td>44.4</td>
<td>40%</td>
</tr>
</tbody>
</table>
Solution: a non-circular camera

Shadowing ~ 15%

MACHETE: a transit wide FOV IACT
MACHETE = Meridian Atmospheric CHETrenkov Telescope

Camera: rectangle of 60° (following the meridian, from south to north) x 5°. Equipped with ~15000 pixels.

Effective D=12m, f=17m (f/D=1.42)

Mirror: Spherical shape (spherical facets following general spherical shape). PSF $r_{80\%} = 0.06°$
Field of view

The whole sky = 42000 deg$^2$

Instantaneous (300 deg$^2$)

Field of View (FOV) of a typical IACT (HESS ~20 deg$^2$, CTA-SCT~50 deg$^2$)

MACHETE: a transit wide FOV IACT
Don’t move the telescope! Move the sky!

The whole sky = 42000 deg²

One year (~20000 deg²)
MACHETE = stereo array
Optical parameters

We’ve optimized some of these parameters using the ray-tracing program ZEMAX and used it to calculate the PSF (which btw is not gaussian)

<table>
<thead>
<tr>
<th></th>
<th>$D=12m$, $f=17m$, $f/D=1.42$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate scale</td>
<td>300 mm/deg</td>
</tr>
<tr>
<td>PSF $r_{80%}$</td>
<td>0.06° for whole FOV</td>
</tr>
<tr>
<td></td>
<td>(MAGIC: 0.07° on-axis — 0.16° at 1.8° off-axis,</td>
</tr>
<tr>
<td></td>
<td>MST: 0.02° on-axis — 0.07° at 2.8° off-axis)</td>
</tr>
<tr>
<td>$\Omega_{\text{pix}} \sim 2r_{80%}$</td>
<td>0.16° = 48 mm</td>
</tr>
<tr>
<td>Total mirror surface</td>
<td>619 m²</td>
</tr>
<tr>
<td>Mirror surface viewed by a pixel</td>
<td>113 m²</td>
</tr>
<tr>
<td>Camera FOV</td>
<td>$60° \times 5° = 300$ deg²</td>
</tr>
<tr>
<td>Number pixels</td>
<td>~15 000</td>
</tr>
<tr>
<td>On-axis shadowing</td>
<td>16%</td>
</tr>
<tr>
<td>$\Delta t_{\text{max}}$</td>
<td>3 ns</td>
</tr>
</tbody>
</table>

MACHETE: a transit wide FOV IACT
Camera

- 5°: ~35 pixels, 1.5m
- 60°: ~400 pixels, 18m

MACHETE: a transit wide FOV IACT
Photosensors

- We have not selected a specific photosensor.
- **PMTs** are standard in IACTs and reach QE>~40% these days, but they are expensive (~300 € / unit) and bulky.
- **Silicon PMs** (aka G-APDs) deliver even higher QE, would cost ~200 € for a MACHETE pixel (assuming 1 $/mm²) and would allow smooth observations with strong Moon (important for such a telescope), but spectral response not optimal and unavailable for the necessary pixel size.
Readout

• Showers have a typical size ~<1°, so we only need to read out a small fraction of the camera (2° x 2° = 256 pixels?).
• A fast local trigger identifies those channels and selects a Region of Interest (RoI). We only need to digitize/record the RoI.
• A possible solution (R. Paoletti, INFN Pisa): install cheap digitizers (TARGET5) in all pixels, break up camera in tiles, digitize tile if local trigger, keep only digitized information if stereo trigger.
• Challenge: 9 kHz proton stereo trigger rate (but each CTA-SCT has 11k pixels and is designed for 10 kHz trigger rate).
Monte Carlo simulation

- We’ve made a full MC simulation of the instrument using the MAGIC MC and analysis software (thanks, MAGIC!!).

- We simulated a 4x4 deg$^2$ section of the camera and a section of the spherical mirror with estimated PSF ($r_{80\%}=0.08^\circ$, considering facet misalignment).

- We assumed basically the same performance of MAGIC for all optical (PSF…) and electronic elements (noise, sampling…), except for PMT QE, which we increased by 50% (consistent with available PMTs).
Sky accessible by MACHETE

- Every object in ~half of the sky drifts through the camera of MACHETE along a year.
- In one year we integrate ~15 hours for each of these objects.
- Objects in ~¼ sky spend about 20 minutes every night in the FOV of the telescopes.
Performance

Integral Sensitivity:
- Reaches 0.77% C.U. after 5 year survey.
  ➔ Similar to planned CTA 1000h survey.
- 1yr survey better than HAWC 5yr survey.
- 1 night sensitivity: 12% CU.

Angular resolution: 0.1° and spectral resolution: 20-15% (standard IACT, much better than HAWC)

MACHETE: a transit wide FOV IACT

Astrop. Physics, in print, and arXiv:1507.02532
Performance

Integral Sensitivity:
- Reaches 0.77% C.U. after 5 year survey.
  ➔ Similar to planned CTA 1000h survey.
- 1yr survey better than HAWC 5yr survey.
- 1 night sensitivity: 12% CU.

Angular resolution: 0.1° and spectral resolution: 20-15%
(standard IACT, much better than HAWC)

Astrop. Physics, in print, and arXiv:1507.02532

MACHETE: a transit wide FOV IACT

The Future of Research on Cosmic Gamma Rays
Physics with MACHETE

- A survey of half of the sky:
  - New Active Galactic Nuclei (Fermi 2FHL: about 230 AGNs detected >50 GeV, most of them not detected by IACT yet).
  - New galactic sources, especially if built in the south.

... and the unknown:
- “Dark sources” = sources emitting only in VHE.
  - Hadronic AGNs
  - Dark matter clumps?
- New types of transients.
- Valuable archive: would provide years-long data sample for phenomena discovered in the future (periodicities, transients)

- Monitor bright VHE sources:
  - Unbiased light curves of AGN and galactic sources.
  - Establish unknown duty cycles (e.g. IC-310).
  - Trigger CTA and other telescopes.
Cost: very rough estimate

- We can use standard IACTs like CTA MSTs to reach the same performance. Is MACHETE cheaper?

  - Good:
    - No need for steering mechanics. Hardly any moving parts: reduction in construction cost and cheaper maintenance.
    - Mirrors or camera can be heavier: assuming 1k€/m² for mirrors (M. Mariotti, M. Doro, INFN Padova), it’s only 1.2 M€ for two telescopes.

  - Bad:
    - 30000 pixels for two telescopes!
    - Number of pixels similar to CTA-SCT. Assuming similar readout, from SCT cost estimate we estimate 1.5 M€ for readout of two telescopes.
    - Significant cost of photosensors: 5.4 M€ for two telescopes assuming 1 $/mm².
    - All in all we estimate ~10 M€ capital cost for two telescopes.
    - Compare to MSTs/SCTs: >3 times cheaper for same FOV.
Discussion/conclusions

- We have found a simple optical solution to build a very wide FOV IACT (300 deg² with PSF r₈₀%=0.06° for D=12m and f/D=1.42).
- Implemented as 2 meridian telescopes, it reaches 0.77% CU integral sensitivity for ~half of the sky in 5 years and 12% CU in a night.
- Very rough cost estimate: 10 M€ for two telescopes.
- Main physics goals: discovery through survey (serendipity!), trigger of transient VHE sources.
Thanks!
The Future of Research on Cosmic Gamma Rays

MACHETE: a transit wide FOV IACT
Can we make an IACT with a much wider FOV?

The most popular optics for IACTs are:

- **Spherical** reflector shape, with spherical facets parallel to the sphere: Too strong spherical aberration

- **Parabolic** reflector shape, with spherical facets parallel to the parabola: No spherical aberration, no aberration for small off-axis angle, but coma for large off-axis. Good timing.

- **Davies-Cotton**, with spherical facets not parallel to the sphere, but pointing at 2*R: Moderate aberration at all off-axis angles. Worse timing.

MACHETE: a transit wide FOV IACT
Can we make an IACT with a much wider FOV?

The most popular optics for IACTs are:

- **Spherical** reflector shape, with spherical facets parallel to the sphere: spherical aberration

- **Parabolic** reflector shape, with spherical facets parallel to the parabola: No spherical aberration, no aberration for small off-axis angle, but coma for large off-axis. Good timing.

- **Davies-Cotton**, with spherical facets not parallel to the sphere, but pointing at 2*R: Moderate aberration at all off-axis angles. Worse timing.

MACHETE: a transit wide FOV IACT

MAGIC, HESS-II, LST

VERITAS, HESS-I, MST

The Future of Research on Cosmic Gamma Rays
Can we make an IACT with a much wider FOV?

**MST:**

- Pretty large FOV $\varnothing=7^\circ$.
- Davis-Cotton mount with $f=16$ m, $D=12$ m ($f/D=1.35$).
- Pixel size=0.18°.
- PSF: $r_{80\%}=0.015^\circ$ on-axis going up to $0.07^\circ$ for off-axis=$2.8^\circ$. Beyond that off-axis angle, PSF grows fast.

MACHETE: a transit wide FOV IACT
Detailed comparison to CTA

- MACHETE (stereo=2 telescopes): 10 M€ capital cost, 300 deg².
- 1 MST: 2.2 M€ capital cost, 38 deg² -> need to cover 8x larger FOV and stereo, so comparable cost is 35 M€
- 1 SCT: 2 M$ capital cost, 50 deg² -> need to cover 6x larger FOV and stereo, so comparable cost is 32 M$