Physics with CTA

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Tim Greenshaw, Liverpool University, on behalf of CTA
Introduction

- Over 140 $\gamma$-ray sources known.
- ~ 90 galactic.
- ~ 115 found with IACTs.
- Further progress requires:
  - Improved sensitivity.
  - Better energy and...
  - ...angular resolution.

Source Types

- PWN
- XRB PSR Gamma BIN
- HBL IBL FRI FSRO LBL AGN (unknown type)
- Shell SNR/Molec. Cloud
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN WR
CTA performance goals

- Aim for factor of 10 improvement in sensitivity.
- Compare HESS ~ 500 hour image of galactic plane...

...with expectation with increased sensitivity, same exposure.

- Expect to observe around 1000 sources (galactic and extra-galactic).
CTA performance goals

- Improve angular resolution by factor ~ 5.
- Substructure of SNR shock fronts can then be resolved:

  - SN 1006:
    - CTA resolution ~ 0.02°.
    - HESS resolution ~ 0.1°.
CTA performance goals

- Better understand energy dependent morphology of pulsar wind nebulae.
- HESS J 1825-137, size of emission region decreases with energy:

$>2.5\,\text{TeV}$
$1-2.5\,\text{TeV}$
$<1\,\text{TeV}$

- Map activity on sub-minute timescales.
- Determine size of emission regions around active galactic nuclei.
- Study quantum gravity.
- Need fast slewing (20 secs), but also large FoV (Fermi $\gamma$-ray burst monitor, has precision $\sim 10^\circ$).
CTA performance goals

- Increase field of view w.r.t. current instruments by factor ~ 2 to 4.5...9°.
- Detect and map extended sources.
- Improve survey capability: galactic plane at ~ 0.001 Crab in 250 hours, full sky at ~ 0.01 Crab in 1 year, > 200 times faster than HESS.

**Southern array:**
- Galactic and extragalactic sources.
- 20 GeV...100 TeV.
- Angular resolution 0.02...0.2°.

**Northern array:**
- Mainly extragalactic sources.
- 20 GeV...1 TeV.
Detecting Cherenkov radiation from air showers

- VHE $\gamma$ causes electromagnetic shower with max. at height $\sim 10$ km.
- Cherenkov angle $\sim 1^\circ$: get light pool on ground with radius $\sim 120$ m.
- Cherenkov emission, attenuation in air, QE of PM lead to:
  - About 1 p.e./m$^2$ in few ns for (frequent) 100 GeV $\gamma$-ray.
  - About $10^3$ p.e./m$^2$ in few 10 to 100 ns for (infreq.) 10 TeV $\gamma$-ray.
- Limitations:
  - $E < 100$ GeV, NSB.
  - $E \sim 0.1...5$ TeV, CR BG ($\gamma/h$ sep).
  - $E > 5$ TeV, rate.
- Need array of different telescopes.
The Cherenkov Telescope Array concept

Low energy
Four 23 m telescopes
4.5° FoV
~2000 pixels
~ 0.1°

Medium energy
About twenty-five 12 m telescopes
8° FoV
~2000 pixels
~ 0.18°

High energy
About seventy 4 m telescopes
9° FoV
1000…2000 pixels
~ 0.17°…0.23°
CTA sensitivity

![Graph showing differential sensitivity (C.U.) for Array I, 50 hours, 5 sigma, LST, MST, SST, and all cases. The graph indicates background and systematics limited, background limited, rate (area) limited, and energy vs. differential sensitivity (C.U.).]
**Large size telescope design – LST**

- Diameter 23 m, focal length 28 m.
- (Modified) Davies-Cotton optics.
- Support structure carbon fibre.
- Camera diameter ~ 2.2 m, mass ~ 2 t, uses conventional 1.5 inch (super-bialkali) photomultipliers.
- Similar to that for HESS II:
Medium size telescope design – MST

- Diameter 12 m, focal length 17 m.
- Davies-Cotton optics.
- Camera support and dish structure steel.
- Camera diameter ~ 2.2 m, mass ~ 2 t.
Medium size telescope design – SCT

- Dual mirror system, allows better correction of aberrations at large field angles.
- Schwarzschild-Couder optics.
- Primary diameter 11.5 m, secondary diameter 6.6 m.
- Effective focal length ~ 5 m.
- Allows use of small pixels, e.g. multi-anode photomultipliers, silicon photomultipliers.
- Proposed ~ 15 kpixel camera provides coverage to large field angles and ~ 0.06° angular pixel size.
Small size telescope design – SST-1M

- SST-1M:
- $D_1 = 4 \text{ m}$, $F = 5.6 \text{ m}$, $f = 1.4$.
- $D_C = 0.88 \text{ m}$, $\text{FoV} = 9^\circ$.
- $\alpha_{\text{pix}} = 0.24^\circ$, $a_{\text{pix}} = 23 \text{ mm}$.
- Pixel hexagonal SiPM, flat-to-flat size 9.4 mm, light concentrator.
Small size telescope design – GCT

- $D_1 = 4\,\text{m},\, D_2 = 2\,\text{m}$.
- $F = 2.3\,\text{m},\, f = 0.57$.
- $D_C = 0.35\,\text{m},\, \text{FoV} = 9.0^\circ$.
- RoC focal plane 1 m.
- $\alpha_{\text{pix}} = 0.17^\circ,\, a_{\text{pix}} = 6\,\text{mm}$.
- Pixel square MAPM or SiPM, 64 per $52 \times 52\,\text{mm}^2$ module.
Small size telescope design – GCT

- Enclosure
- Lid
- Pointing
- LEDs
- 32 Photosensor modules
- LED Flasher Units
- ~0.4 m
- ~45 kg
- ~450 W

TARGET Module
Preamplifiers
Small size telescope design – ASTRI

- $D_1 = 4.2\, \text{m}$, $D_2 = 1.8\, \text{m}$.
- $F = 2.2\, \text{m}$, $f = 0.51$.
- $D_C = 0.37\, \text{m}$, FoV = 9.6°.
- RoC focal plane 1 m.
- $\alpha_{\text{pix}} = 0.17^\circ$, $a_{\text{pix}} = 6\, \text{mm}$.
- Pixel square SiPM, 64 per $52 \times 52\, \text{mm}^2$ module.
Possible CTA sites

- Southern sites
  - Negotiations starting:
    - Aar.
    - Armazones.
  - Reserve:
    - Leoncito.
- Northern sites
  - Under consideration:
    - Tenerife.
    - San Pedro Martir.
    - Yavapai.
    - Meteor Crater.
Dark matter searches with CTA

- About $\frac{1}{4}$ of energy budget of universe is DM (WMAP...).
- Structure studies imply DM “cold”.
- WIMPs give required DM density...
- ...and can annihilate to give SM particles, including photons.
- $\gamma$ flux from DM annihilation scales with square of DM density along line of sight to source, J.
- Good targets have large J, and small astrophysical $\gamma$-ray foregrounds.
- Galactic centre brightest source, but many AP sources of photons.
- Dwarf spheroidal galaxies close, high DM content, no AP $\gamma$ sources.

- Galactic centre observations (500 hours) with CTA could rule out 50% of WIMPs in pMSSM at 95% CL*.

*Wood et al, arXiv:13050302
Lorentz invariance violation – take one

- Quantum fluctuations may produce “space-time foam” at the Planck scale.
- Refractive index of vacuum may be energy dependent.
- Parameterise dispersion using expansion:

\[ c^2 p^2 = E^2 \left[ 1 \pm \xi_1 \frac{E}{E_{Pl}} \pm \xi_2 \left( \frac{E}{E_{Pl}} \right)^2 \pm \ldots \right] \]

- Observation of \( \gamma \) flares from remote AGNs or GRBs may allow detection of energy dependent time delays*.
- Problem is disentangling source and propagation effects.

Most constraining current results:
- Fermi-LAT observation of GeV photons from GRB 090510 imply

\[ M_1 = \frac{\xi_1}{E_{Pl}} > 1.5 \times 10^{19} \text{ GeV}. \]

- AGN flare (PKS 2155-304) seen by HESS gives

\[ M_2 = \frac{\xi_2}{E_{Pl}} > 6.4 \times 10^{10} \text{ GeV}. \]

- CTA will see more sources, out to larger distances.
- Limits \( M_1 \sim M_{Pl} \) possible, significant improvement in constraints on \( M_2 \).

*Amelino-Camelia et al, Nature 393
Lorentz invariance violation – take two

- HE $\gamma$ rays interact with the EBL (for $E_\gamma > 1$ TeV) and the CMB (for $E_\gamma > 100$ TeV).

- Expect universe to be opaque at the highest energies.

- But if Lorentz invariance is violated, kinematics of pair production change*.

- Opacity decreases again at HE.

- 50 hour observation of Mrk501:

- Depending on assumptions made about source spectrum, allows limits $M_1 \sim M_{Pl}$, $M_2 \sim 5 \times 10^{11}$ GeV.

*Fairburn et al, JCAP06
Searches for axions

- Apparent opacity of universe to HE $\gamma$s also changes if there are axion-like particles.

- E.g. simulation of 5 h flare of PKS 1222+21, see change in spectrum*.

- Allows searches for ALPs in mass, coupling regions not otherwise accessible.

* Doro et al, Astropart Phys 43
CTA will offer significantly increased sensitivity over current imaging atmospheric Cherenkov telescope arrays, coupled with improved energy and angular resolution.

In addition to astroparticle physics studies, CTA will allow investigation of fundamental physics topics including:

- Searches for dark matter.
- Lorentz invariance violation.
- Axion-like particles.