Cherenkov Radiation and Its Application

Group 26

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Brief history of Cherenkov rad.

- Discovered by Pavel Cherenkov 1934
- when studying fluorescence emission induced in uranyl salts

  (ɣ-ray in radioactive source)

- light was emitted even with solvent only
- Explained Ilya Frank & Igor Tamm 1937

Cherenkov radiation theory

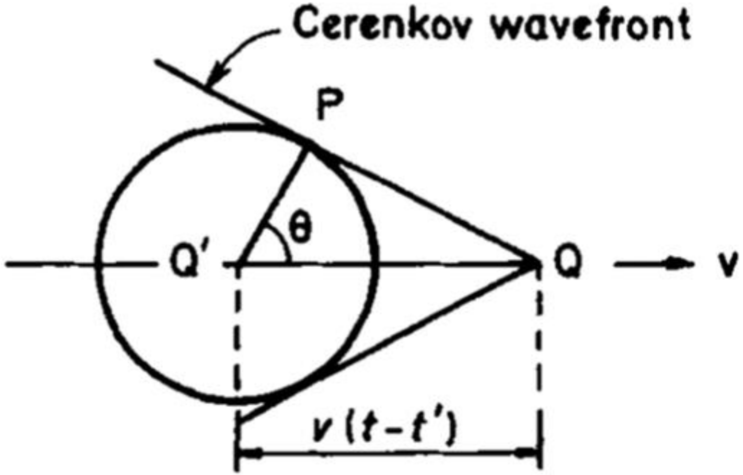
What is Cherenkov Radiation (CR)

- emitted by a high energy charged particle
- with a velocity greater than the light speed in medium
- usually form a forward light cone
- occur when the condition is met:

$$\beta n > 1$$

v/c, ratio of particle velocity to the vaccum light speed

refractive index of medium



A geometric proof of CR

(particle travel from t' to t)

- light path $\mathrm{Q'P} = \frac{c}{n}(t - t')$
- Particle path $\mathrm{Q'Q} = v(t - t')$,
- Emission angle $cos\,\theta = \frac{\mathrm{Q'P}}{\mathrm{Q'Q}} = \frac{c}{vn} = \frac{1}{\beta n}$
- $|\cos\theta|$<=1→ βn > 1

ravel from t' to t)

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|<=1→ βn > 1

CR field in EM theory

- In vacuum: E-field at a field point (time t, charge q, uniform velocity $\mathbf{v}$)

$$\mathbf{E} = \frac{q}{4\pi\varepsilon_0}\frac{\alpha\mathbf{R}}{s^3},$$

where $\mathbf{R}$: radius vector from charge location at time t to the field point,

$$\alpha = \left(1 - \frac{v}{c}\right)^2, \; s = \left[\alpha R^2 + \frac{1}{c^2}(\mathbf{v}\cdot\mathbf{R})^2\right]^{\frac{1}{2}}$$

- In medium (permittivity ε & refractive index n),

$$\alpha \Rightarrow \left(1 - \frac{vn}{c}\right)^2, \; s \Rightarrow \left[\alpha R^2 + \left(\frac{n}{c}\mathbf{v}\cdot\mathbf{R}\right)^2\right]^{\frac{1}{2}}$$

CR field in EM theory

$s = \left[1 - \left(\frac{vn}{c}\right)^2 \sin^2\varphi\right]^{\frac{1}{2}} R$, where φ is the angle between $\mathbf{v}$ and $\mathbf{R}$

- If $v > \frac{c}{n}$, s => imaginary, except for region with $\sin\varphi \leq \frac{c}{vn}$
- Field point must be to the rear of particle
- E-field exist only in a cone, with half angle $\varphi = \arcsin\left(\frac{c}{vn}\right)$, and vertex at the particle location at time t.
- Cone surface = surface of Cherenkov shock wave and contains the Cherenkov radiation field. ($E \to \infty$ on the surface)

CR field in EM theory

- A unit vector $\mathbf{S}$: normal to the upper plane of light cone, and
- $\mathbf{S}$ // $\mathbf{k}$ ($|\mathbf{k}| = \frac{\omega}{c} n$) of the Cherenkov radiation. Then

$k_x = \frac{\omega}{c} n \sin\theta = \frac{\omega}{c} n \left(\frac{c}{nv}\right) = \frac{\omega}{v}$, and

$k_{yz} = \sqrt{\left(\frac{\omega}{c} n\right)^2 - \left(\frac{\omega}{v}\right)^2}$

- If $v < \frac{c}{n}$, k_{yz} will become imaginary => The field will not exist

Threshold particle energy

- E(particle) = $\gamma m_0 c^2$

$$= \frac{1}{\sqrt{1-\beta^2}} m_0 c^2$$

$$>= \frac{n}{\sqrt{n^2-1}} m_0 c^2$$

- For example, in water, E_{thr} ~ 264 keV

  in air , E_{thr} ~ 38GeV

Cherenkov counter

Cherenkov counter

Made by (fitting a long pipe of) medium with an optical system capable of

- detecting the emitted light
- measuring the angle of emission.

Usage:

- With known rest mass/type,
- Measurement of the Cherenkov angle => Measurement of the particle momentum/speed.
- Or vice versa

Imaging atmospheric Cherenkov telescope (IACT)

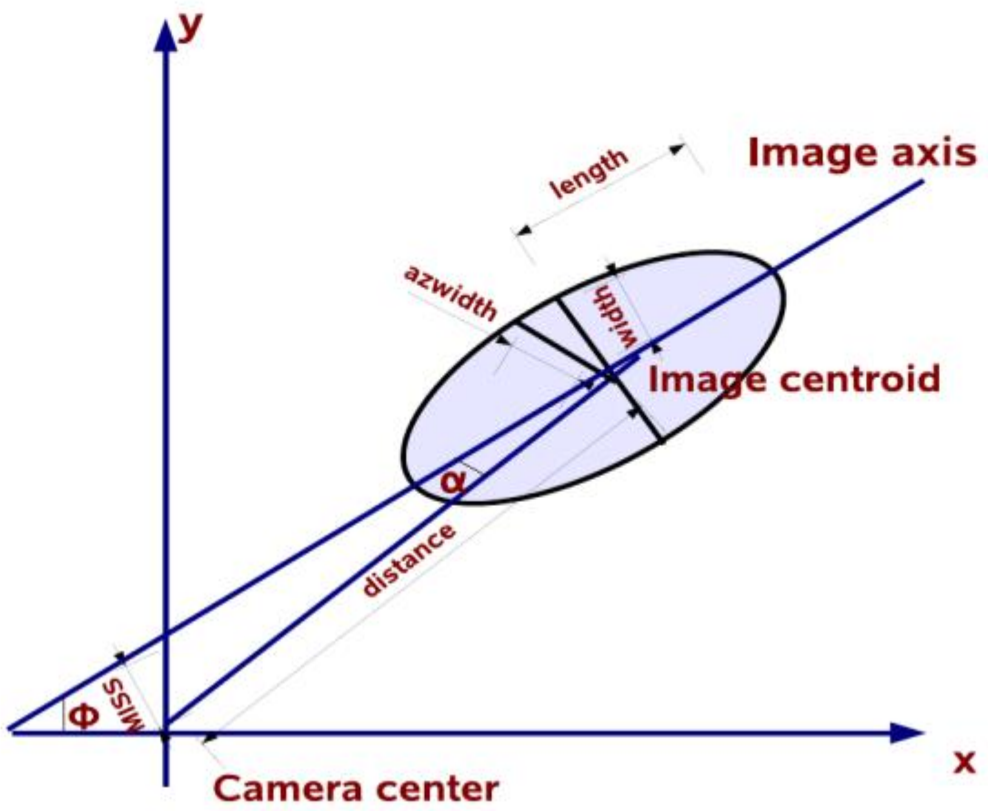
Working principles

- aims at ɣ-ray with 100GeV-20TeV
- use the atmosphere as the medium
- high-energy ɣ-ray interact and scatter → produce a shower of charged particles with $v > c_{air}$
- Shower produces Cherenkov pool with r > 100m
- Mirrors on a telescope reflect CR towards a fast-camera (ns) and images are obtained
- light will be captured by sensors and turned into data for later analysis.

Hillas parameters

- Size: sum of photo-electrons (pe) of all PMT channel
- Distance: angular distance of centroid from telescope axis
- Alpha: angle between major axis and telescope axis

- useful in simulations, ɣ/hadrons segregation



thesis.pdf (hbni.ac.in)

Computer simulation

tool: CORSIKA code

- tracks each particale produced in shower, not only ɣ-ray
- outputs particle type, energy, direction etc which can be used in further analysis and simulations

with add-on package,

- able to extract cherenkov photon data from shower data

Primary ɣ-ray direction estimation

For multiple telescopes

- major axis is direction of primary

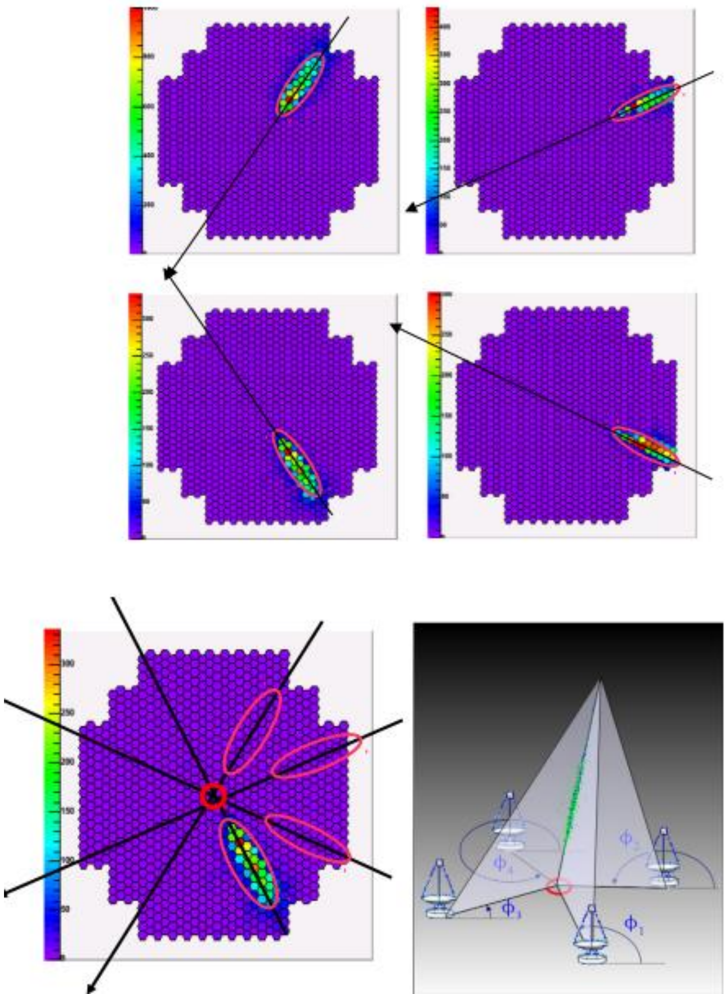
  ɣ-ray projecting onto camera plane

- so ɣ-ray source lies on major axe
- finding the intersecton of major axes

  gives the source position on camera

For single telescope, Disp method is a way

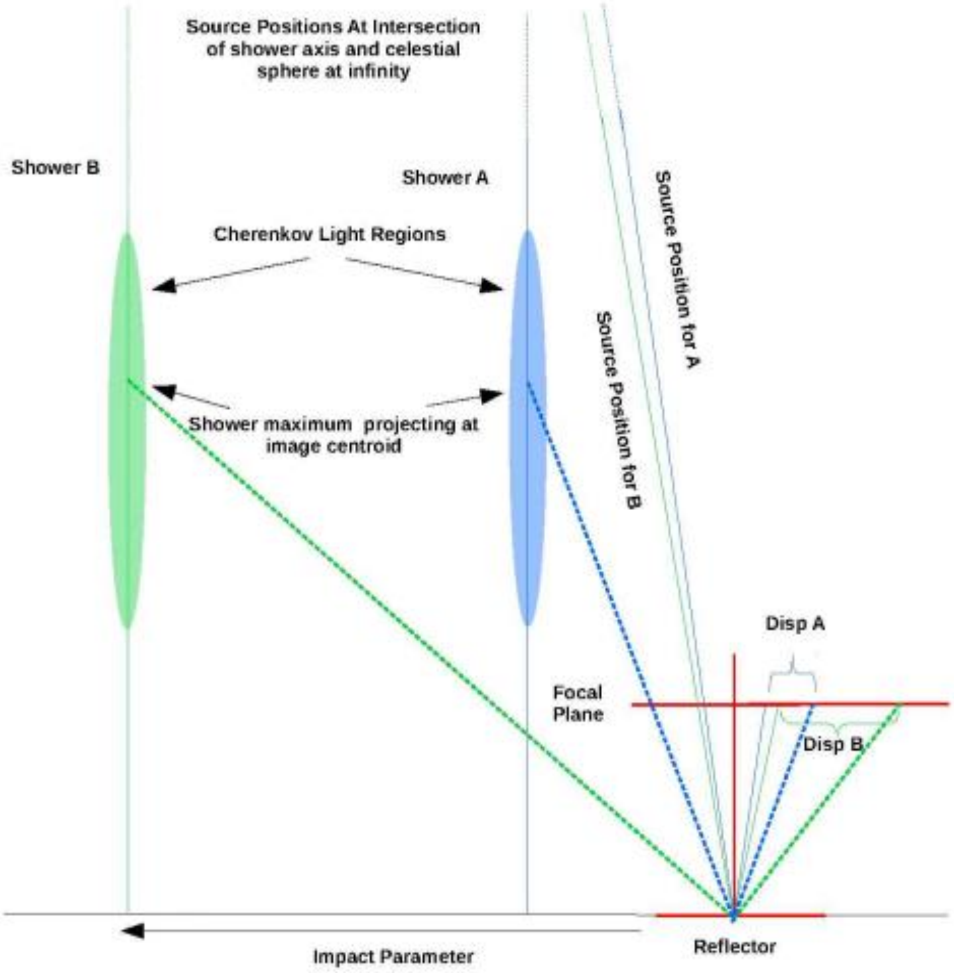
deNaurois+ 2015 C.R. Phys. 16 610



userpages.irap.omp.eu/~ltibaldo/material/IntroCTA_sexten.pdf

Disp method

- angular distance between source position and image centroid
- disp increases with impact parameter, same for elongation (width / length)
- disp-elongation correlation can be estimated by a computer model (RFM regression)



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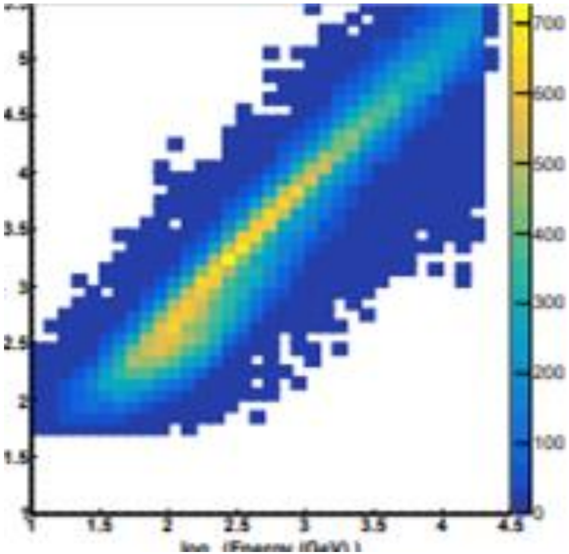
ɣ-ray energy estimation

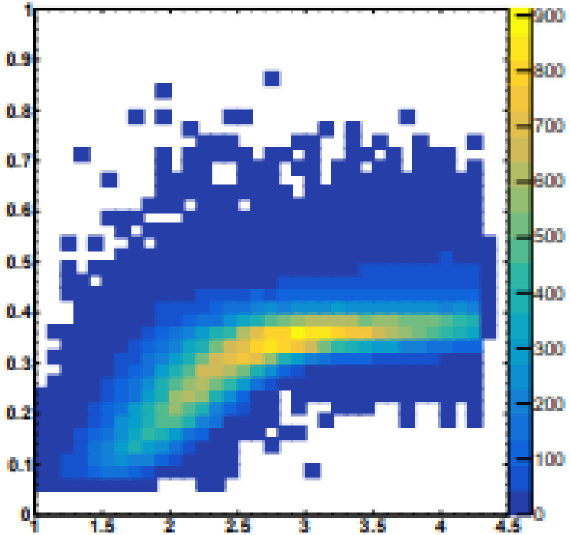
- primary energy relates to Hillar parameters (size, length) => allow estimation
- can also be estimated by RFM regression

log(size[pe])



log(energy[GeV])

length[degree]



log(energy[GeV])

[thesis.pdf (hbni.ac.in)]

Night sky light contribution (LONS)

- raw image of shower contains pe induced by LONS photons which affects sensitivity of telescope
- Measure LONS spectum at nearby site
- To find the contribution of LONS on each pixel per unit time,

$$dN/dt \text{ (1 pixel)} = \left(\int dN/dtdAd\Omega/d\lambda \, d\lambda\right) \times A\Omega\text{(1 pixel)}$$

number of pe (per pixel, LONS)

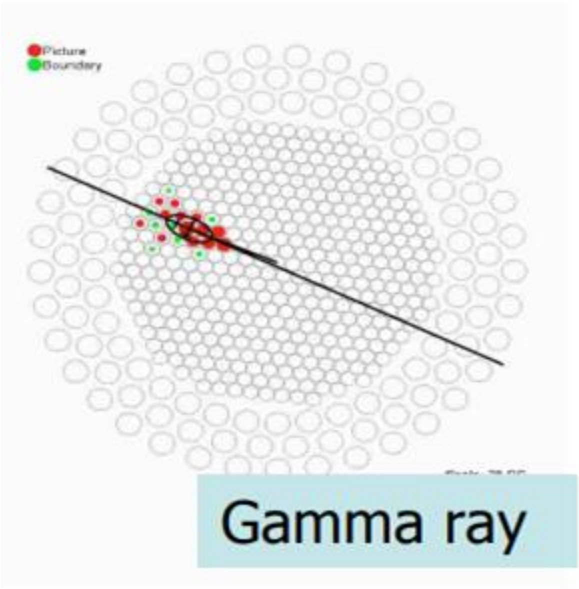
LONS flux spectum

total reflector area

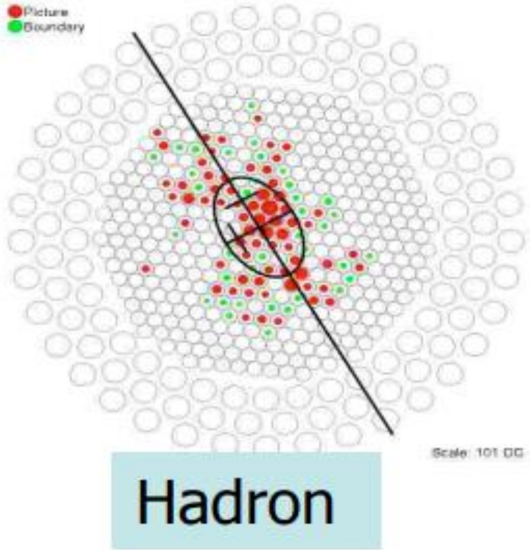
angular size of 1 pixel

(1.46 pe per pixel in 5ns)

Rejection of background cosmic ray



Shorter in width & length



longer in width & length

L801_GammaAstrCherenkov.ppt (wisc.edu)

Rejection of background cosmic ray

Method 1: static cut

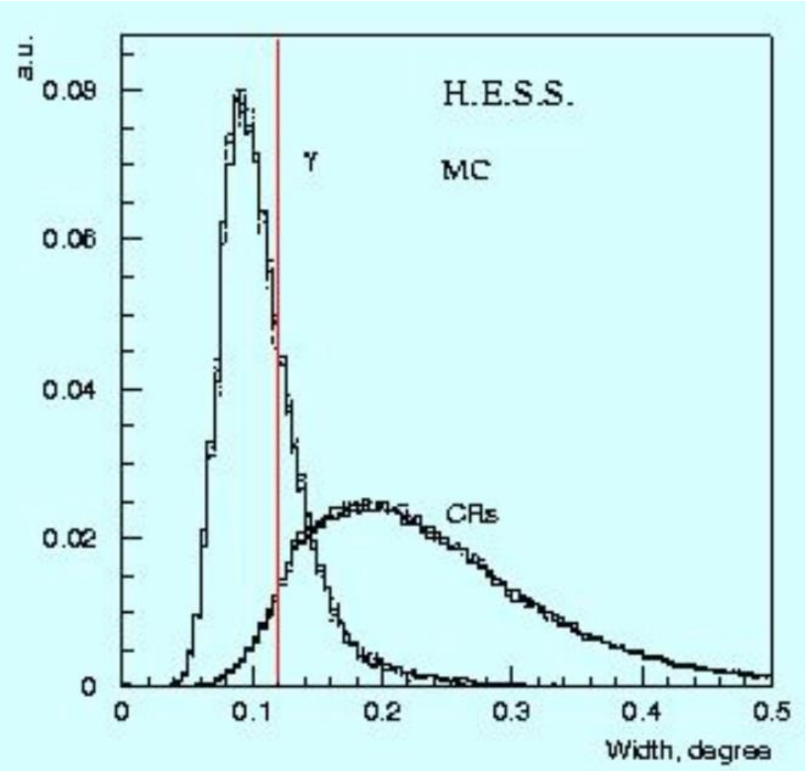
- apply a simple on Hillas parameters

More efficient way: Machine learning

- Trained using data from simulations
- Hillas parameters as input
- Assign a hadronness score

  (likeliness of being a hardon event)

- A cut is applied to the hadronness



Static cut example

L801_GammaAstrCherenkov.ppt (wisc.edu)

New generation ɣ detection telescope

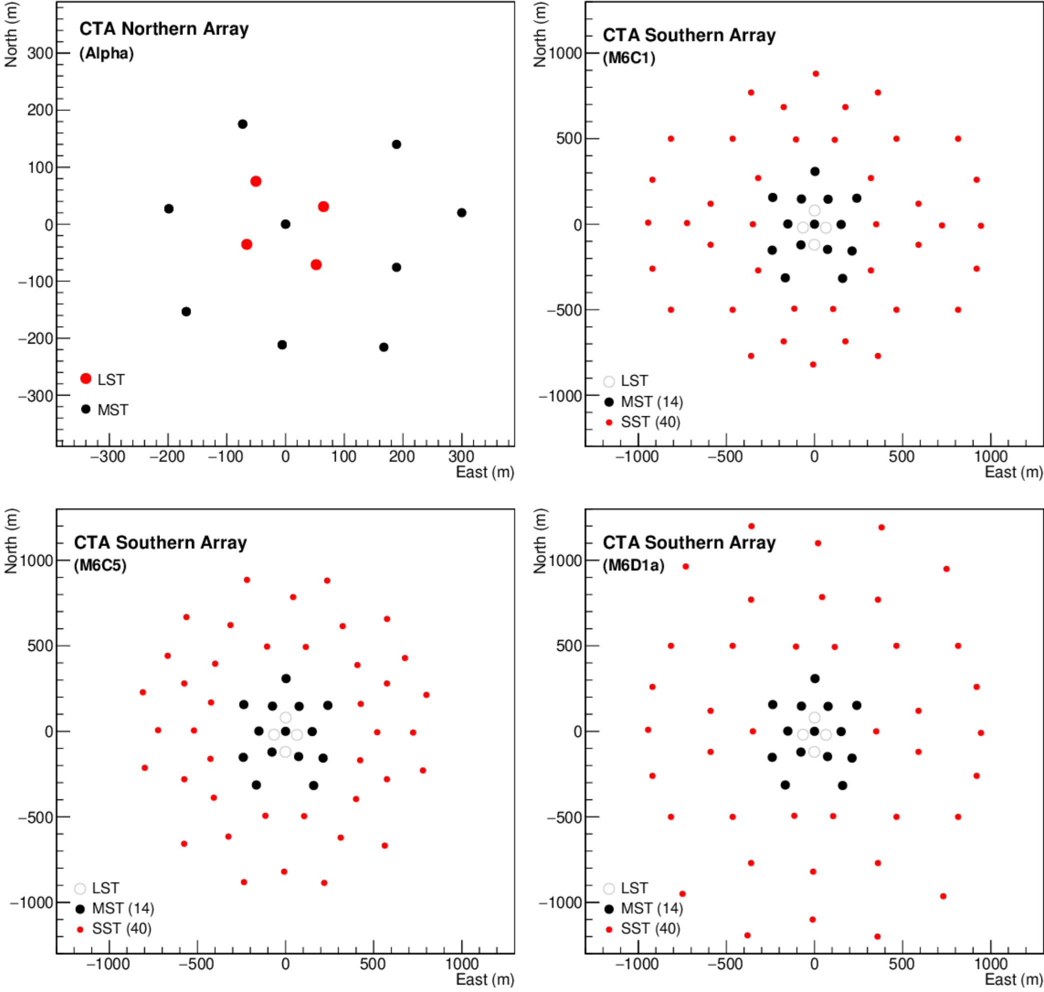
Locations of CTA

Types of telescopes

Large size telescopes: 20-100GeV

Medium size telescopes: 0.1-5TeV

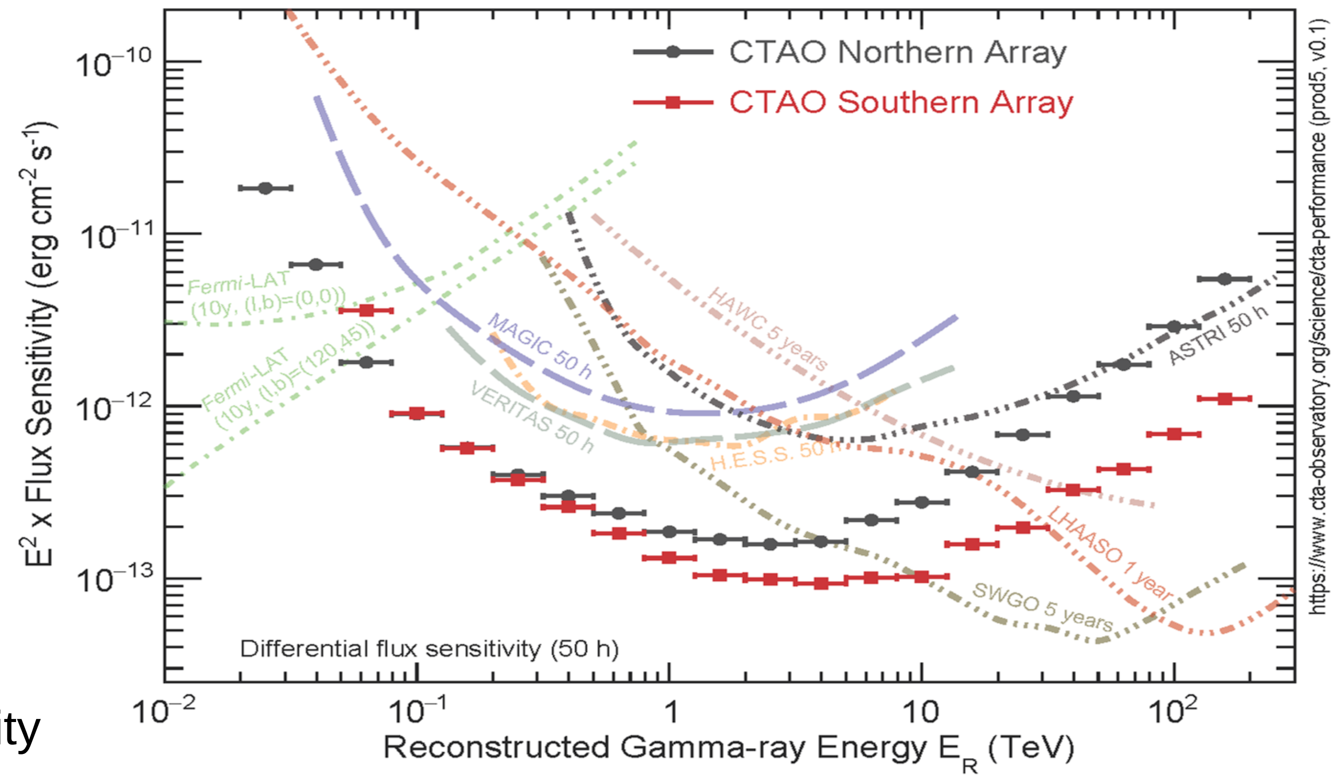
Small size telescopes: 5-100TeV



CTA array arrangement

[[PDF] The Cherenkov Telescope Array: layout, design and performance | Semantic Scholar]

Comparison with CTA and other tools



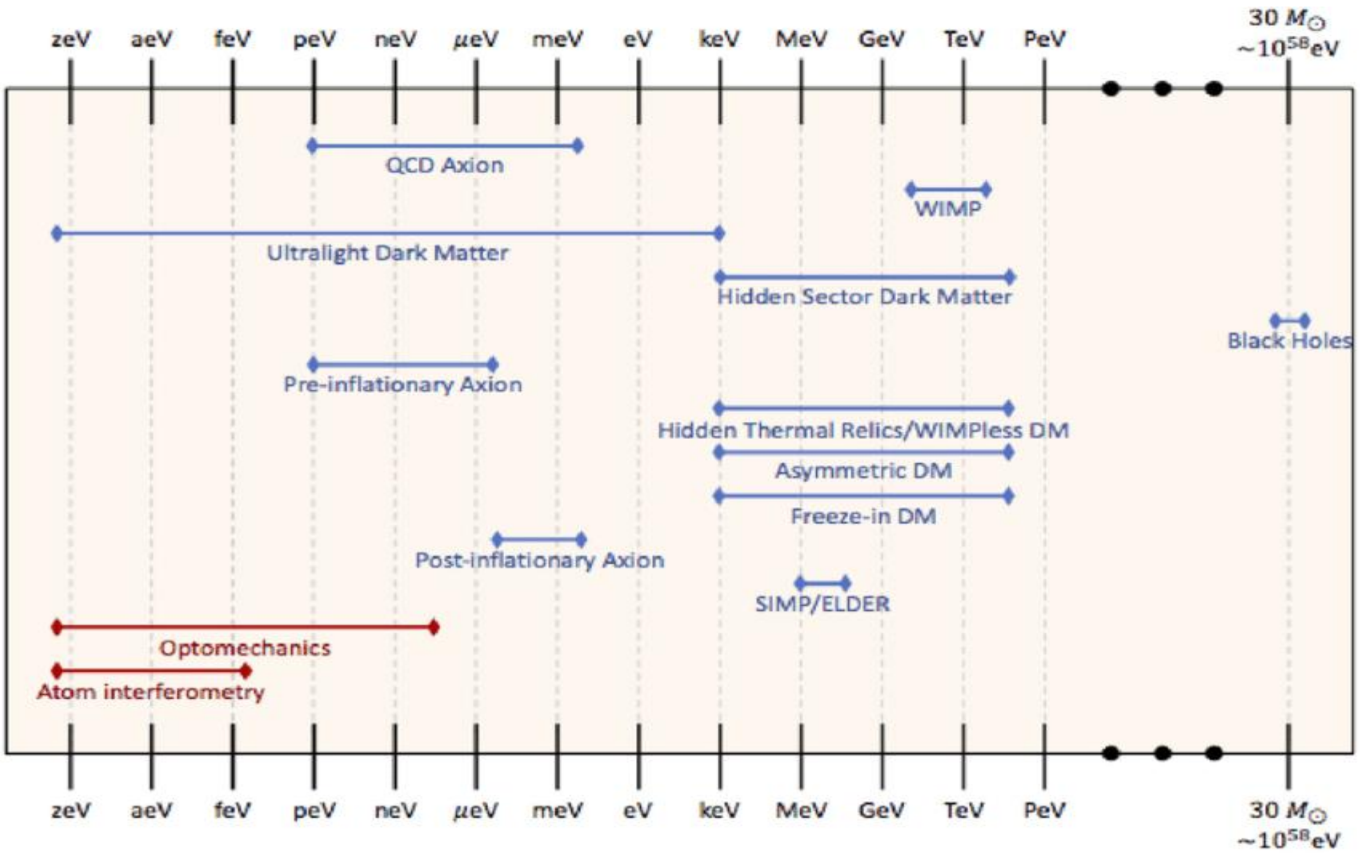
- Sensitivity
- detection range

CTAO Performance - Cherenkov Telescope Array (cta-observatory.org)

Dark matter (DM) detection with CR

Dark matter candidates

(PDF) Quantum physics in space | ResearchGate



Why WIMP?

$$\Omega_\chi h^2 = \frac{3 \times 10^{-27}\ \mathrm{cm^3\ s^{-1}}}{<\sigma_{\mathrm{an}} v>}$$

Cosmological abundance of WIMP

Hubble ratio = H_0/100 km s^{-1} Mpc^{-1}

Weak interaction cross-section, 3 x 10^{-26} cm^3 s^{-1}

- $\Omega\chi$ ~ 0.2, similar to ΩDM ~ 0.27
- Main focus - Neutralino (self-annihilated)

1403.4495.pdf (arxiv.org)

Dark matter annihilation

$$\frac{d\Phi_\gamma}{d\Omega\, dE_\gamma}(E_\gamma, \psi) = \frac{1}{4\pi} \int_{\rm l.o.s} d\ell(\psi)\rho_\chi^2(\mathbf{r}) \left(\frac{\langle \sigma v \rangle_{\rm ann}}{2S_\chi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} \right)$$

differential flux astrophysic factor particle physics factor

where,

- σ = total cross section
- dN/dE is spectrum
- ρ is DM density
- S_χ = 1(self-annihilated) or 2 (else)

pdf (iop.org)

Good detection target

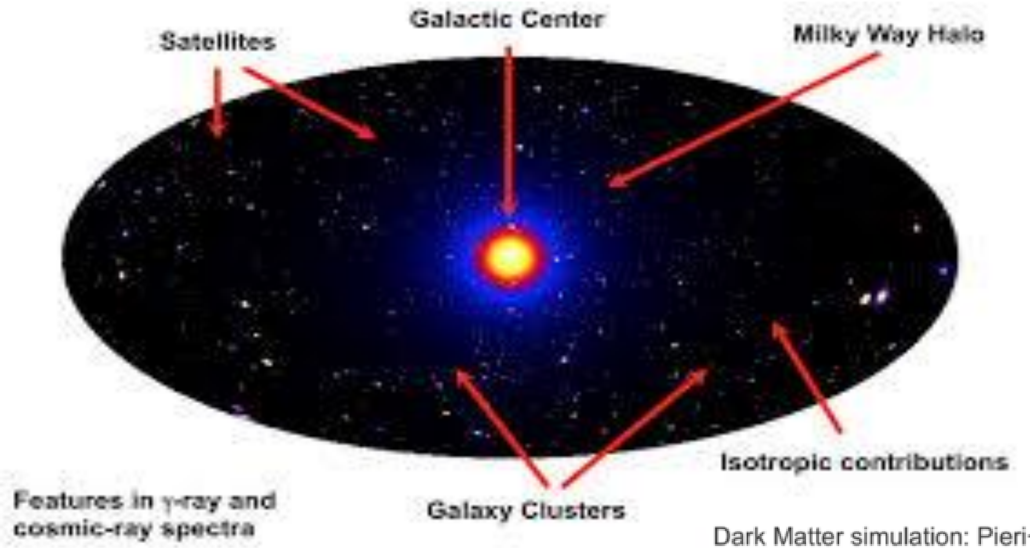
$$\frac{d\Phi_\gamma}{d\Omega\, dE_\gamma}(E_\gamma, \psi) = \frac{1}{4\pi}\int_{\rm l.o.s} d\ell(\psi)\rho_\chi^2(\mathbf{r}) \left(\frac{\langle \sigma v \rangle_{\rm ann}}{2 S_\chi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} \right)$$

To maximize γ flux, we need to look for:

- a close ($\propto d\Omega$),
- DM-dominated system ($\propto \rho^2$)

=> Galactic centre

Targets for DM detection (CTA)



Dark Matter simulation: Pieri+ 2011PhRvD..83b3518P

FelliniWorskshop_dimauro (infn.it

Noise suppression

Major noise: Strong γ-ray background (almost isotropic)

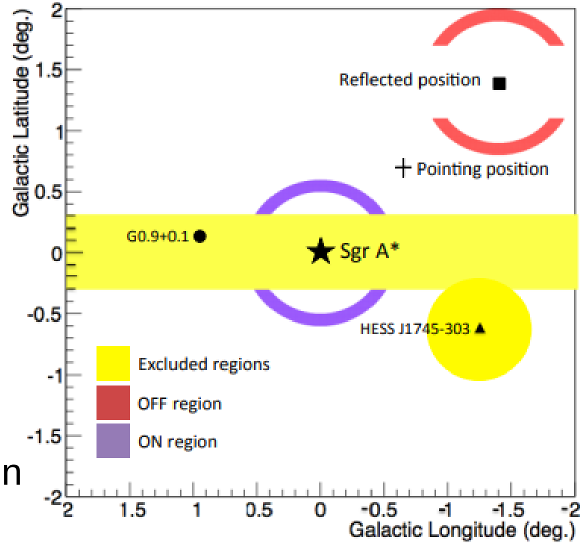
Solutions:

- Observe γ-ray background from other position that are believed without DM
- Build emission model to predict γ-ray emission without DM

Also, when detecting galactic center,

- exclude areas around the galactic core,
  as γ-flux is too high.

(by massive stars, neutron stars etc.)



Galactic center detection region (HESS)

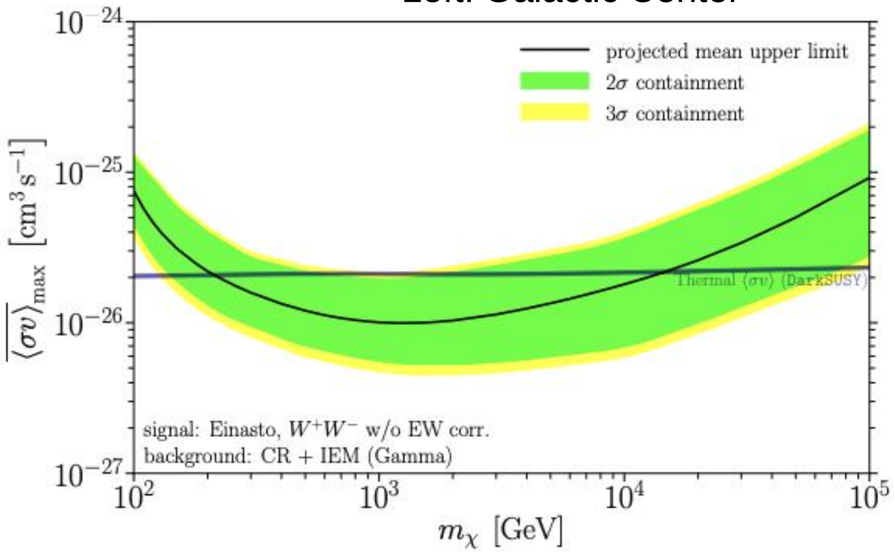
1607.08142.pdf (arxiv.org)

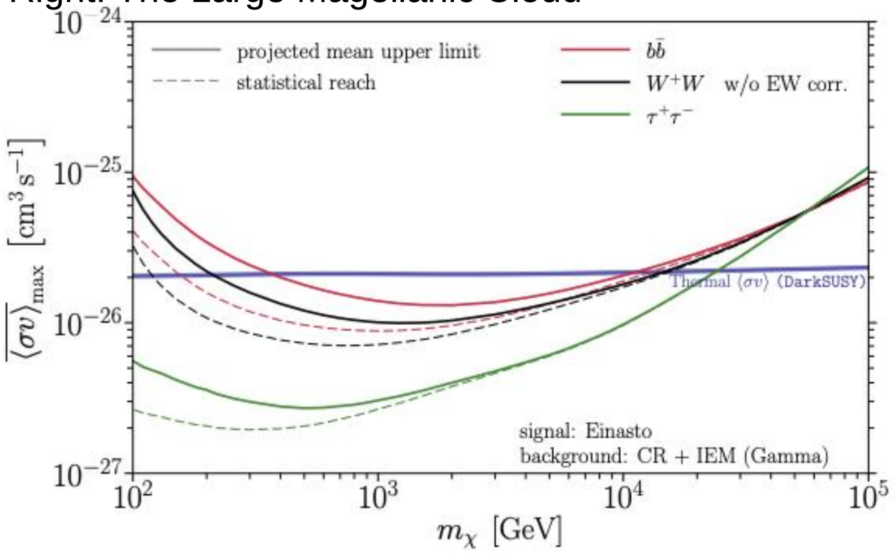
Sensitivity of CTA in DM detection

Sensitivity curves to a DM annihilation signal for different DM model

Left: Galactic Center

Right: The Large Magellanic Cloud





pdf (iop.org)

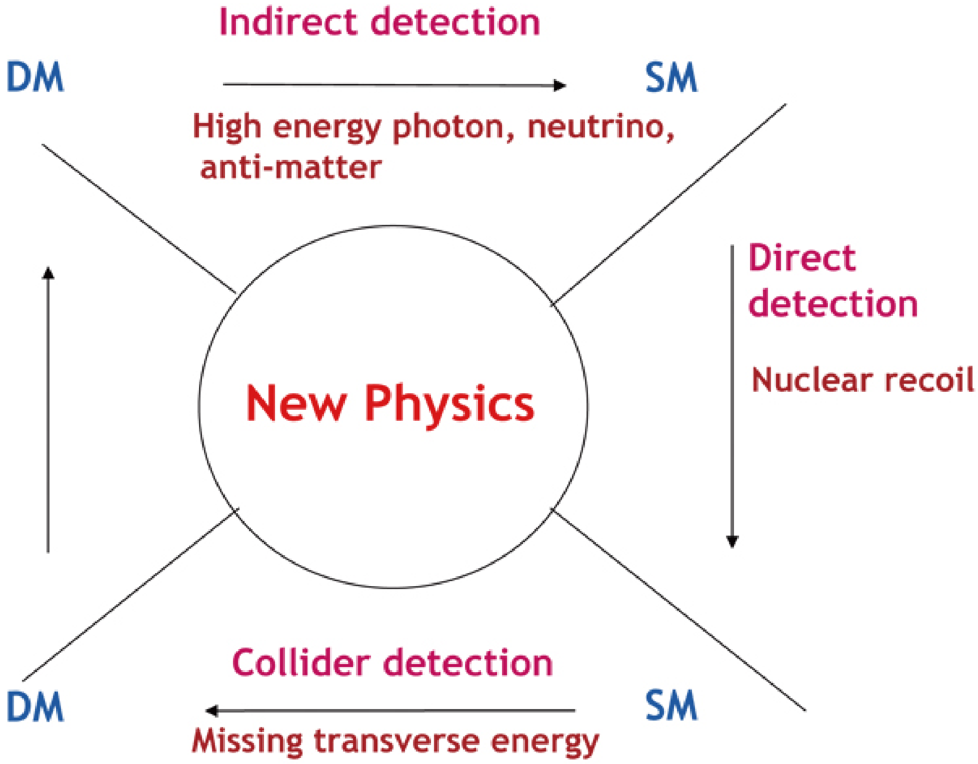
Comparison of other methods

- Direct detection:

  Signal for DM particle << noise, mostly builded underground

- Collider detection:

  High energy input, can be studied in detail



3 current categories in DM detection

[Detection of Dark Matter Particles and Progress*----Bulletin of the Chinese Academy of Sciences (cas.cn)]

Conclusion

Conclusion

- Occurs when charged velocity >> light speed in medium
- Can be detected by Cherenkov counter
- Useful in astrophysics (CTA, DM detection etc)

Thanks for listening and Q&A!