CTA: Gamma line emission searches

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Outline

- Introduction - Dark matter and indirect search using gamma rays
- Where to look? - Astrophysical targets
- Gamma ray flux expectations
- The instrument - Cherenkov Telescope Array
- Simulation study - CTA sensitivity to gamma line emissions
- Related results from Fermi-LAT
- Outlook

The case for dark matter

While the standard model of particle physics works well for all high-energy experiments; astrophysical studies indicate that in addition to ordinary matter, our universe contains some particle with mass, but that interacts very weakly with matter. This is termed "Dark matter".

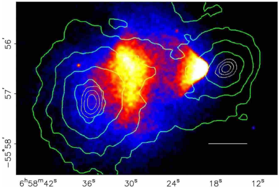
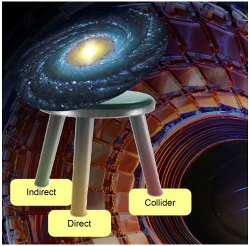


Figure: 1EO657-558, the bullet cluster, showing X-ray emission in color and gravitational potential as lines [2]

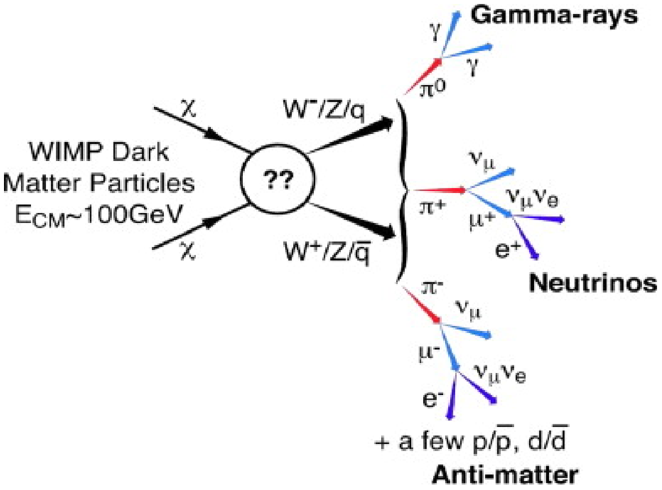
[1] http://arxiv.org/abs/astro-ph/0608407
[2] http://arxiv.org/abs/astro-ph/0608407

Indirect search for dark matter

- Additional evidence and identification of dark matter may be obtained by detecting decay/annihilation products
- Different messenger particles may be looked for
  - antimatter (PAMELA, AMS-02, . . .)
  - neutrinos (IceCube, ANTARES, . . .)
  - gamma rays (Fermi-LAT, CTA, . . .)
- Indirect searches are complementary to direct and collider searches

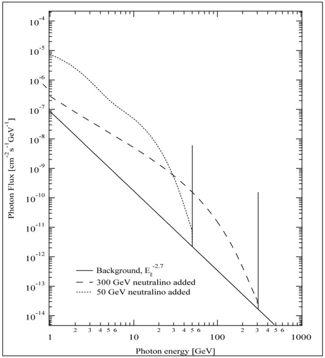


Indirect search for dark matter



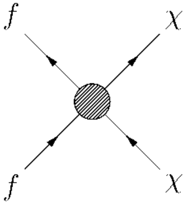
Dark matter self-annihilation

- The DM candidate in many models is a Majorana particle
  - pair annihilation is possible: $\chi\chi \rightarrow$ something
- Most final states which includes a photon yields an enhancement of the gamma ray flux over a broad energy range with an endpoint that depends on the DM particle mass
  - difficult signal to pick out from the background
  - difficult to prove that the enhancement is due to DM
- The annihilation channel $\chi\chi \rightarrow \gamma\gamma$ yields monoenergetic gamma photons with energy equal to the DM particle mass
  - very distinct signal – smoking gun
  - weak signal, $BF \sim 10^{-3}$ in most models



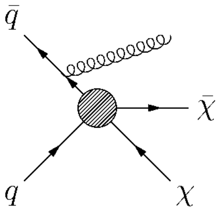
Mono-jets and mono-photons in accelerator searches

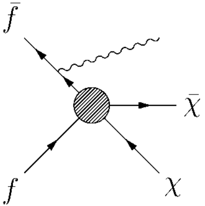
- If pair-annihilation of DM particles is possible, pair-production should also be possible
- But with no visible particles produced, the events will not be seen in an accelerator search



Mono-jets and mono-photons in accelerator searches

- If pair-annihilation of DM particles is possible, pair-production should also be possible
- But with no visible particles produced, the events will not be seen in an accelerator search
- But if a photon or a jet is created through initial or final state radiation, the process may be triggered on



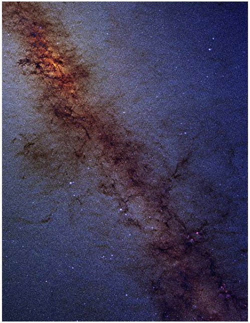


Where to look? Potential astrophysical targets

- The optimal candidate for a target region to detect DM has:
  - high DM density, signal strength $\sim \rho_\chi^2$
  - low gamma ray background from other sources

Where to look? Potential astrophysical targets

- Galactic centre region
  - highest DM density in our galaxy
  - non-negligible gamma ray background



Where to look? Potential astrophysical targets

- Galactic centre region
  - highest DM density in our galaxy
  - non-negligible gamma ray background
- Dwarf spheroidal galaxies
  - in many cases much larger DM-to-ordinary matter ratio than in the Milky Way or it's centre
  - generally no gamma ray sources – only background is the diffuse gamma ray emission seen from all of the galaxy
  - smaller DM density than the galactic centre ⇒ weaker signal

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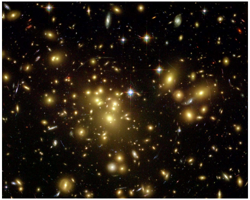
- Galaxy clusters
  - large expected flux
  - large spatial extent is a challange for cherenkov telescopes



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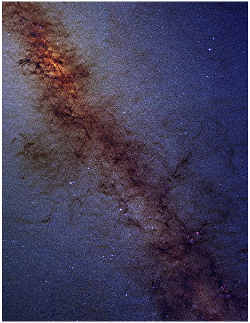


Gamma ray flux from DM annihilation

- Flux from a direction part of the sky[3]:

$$\Phi = \frac{v\sigma}{2\pi M_\chi^2} \cdot \int_{\Delta\Omega} d\Omega \int_{\text{line of sight}} \rho^2(l) dl$$
$$= (\text{particle physics factor}) \cdot (\text{astrophysics factor})$$

[3] http://arxiv.org/abs/astro-ph/9712318v1

DM density in the galactic centre

- DM density in the galaxy is fairly well known from observations, but the centre is not resolved in neither observations nor simulations
- Popular models:
  - Navarro-Frenk-White (NFW)[4]

$$\rho = \frac{\rho_s}{\frac{r}{R_s}\left(1+\frac{r}{R_s}\right)^2)}$$

  - Einasto[5]

$$\rho = \rho_s e^{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]}$$

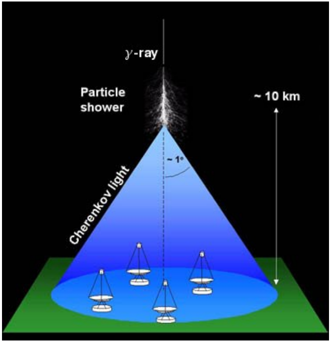
  - Isothermal[6]

$$\rho = \frac{\rho_s}{1+\left(\frac{r}{r_s}\right)^2}$$

[4] http://arxiv.org/abs/astro-ph/9611107
[5] Einasto, Trudy Inst. Astroz. Alma-Ata 51, 87 (1965)
[6] Bahcall and Soneira, Astrophys. J. Suppl. 44, 73 (1980)

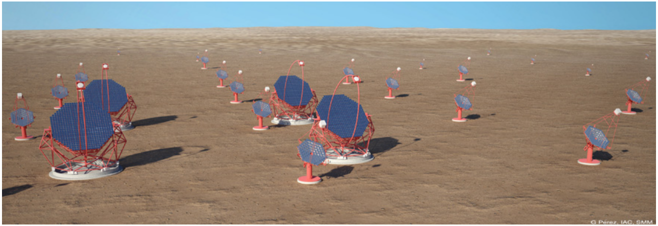
Imaging Atmospheric Cherenkov Telescope (IACT)

- IACTs are ground based observatories that detect Cherenkov radiation emitted by the shower initiated by cosmic gamma rays hitting the atmosphere
- The technique allows detection of gamma rays in the range $\mathcal{O}(10 GeV)$ to $\mathcal{O}(100 TeV)$
  - some overlap with satellite observatories such as Fermi-LAT, but more focus on higher energies
- Stereo vision obtained by having two or more telescopes yields directional information of the incoming gamma photon



Cherenkov Telescope Array (CTA)

- The CTA project is an initiative to build the next generation ground-based very high energy gamma-ray observatory
- CTA will consist of two telescope arrays – one in each hemisphere
- The increased number of telescopes compared to present observatories will
  - increase number of detected gamma rays
  - improve angular resolution
  - improve cosmic ray background supression
- UiB is a part of the preparatory phase (ongoing)

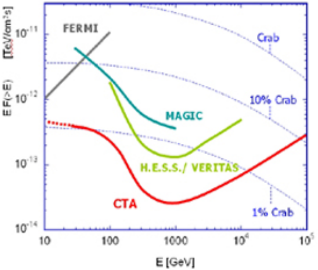


The CTA consortium

- Members
    - 27 nations
    - 154 institutions
    - 1000 people
- CTA is currently in the preparatory phase
    - Started in October 2010
    - Investigation of science possible with CTA
    - Site selection
    - Technical options

CTA science

- CTA has a broad science program:
  - Cosmic ray origin and acceleration
  - Pulsar wind nebulae
  - The galactic centre region
  - Microquasars, gamma-ray-, and x-ray binaries
  - Stellar clusters, star formation, and starburst galaxies
  - Pulsar physics
  - Active galaxies, cosmic radiation fields and cosmology
  - Gamma-ray bursts
  - Galaxy clusters
  - Dark matter and fundamental physics
  - Imaging stars and stellar surfaces
  - Measurements of charged cosmic rays



- CTA is expected to both largely increase the number of known gamma ray sources in the sky, and processes generating the gamma rays

Simulation study of the sensitivity to gamma ray line emission

- The present study aims to evaluate the sensitivty to gamma ray line emission for a set of proposed array layouts
- Target region is the galactic centre where MAGIC has measured the gamma ray background:[7]

$$\Phi = \Phi_0 E^{-2.1} e^{-E/15.7\,TeV}$$

- The analysis is performed unbinned using a profile likelihood approach

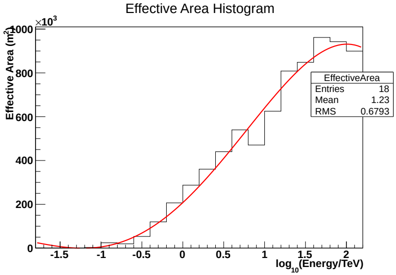
[7] http://arxiv.org/abs/0906.1247

Effective area

- The shower radius scales with the energy of the incoming gamma ray
  - effective area for detecting gamma rays increases with increasing energy
  - number of received photons per energy has two energy dependent factors:

$$\frac{dN}{dE} = \Phi(E) \cdot A_{eff}(E) \cdot t$$

- Effective area is estimated using a Monte Carlo simulation
  - need different simulations for different array layouts
- The present analysis fits the effective area histogram with a 4th degree polynomial to get a smooth function



Profile likelihood analysis

- Likelihood function:

$$L(\{E\}|f, m_\chi, \Gamma) = f \cdot S(E_i, m_\chi) + (1 - f) \cdot B(E_i, \Gamma)$$

  - f: signal fraction, contrained to the interval [0,1]
  - Signal PDF:

$$S \propto A_{eff}(E_i) \cdot e^{-(E_i - m_\chi)/E_{res}^2(m_\chi)}$$

  - Background PDF:

$$B \propto A_{eff}(E_i) \cdot E_i^\Gamma$$

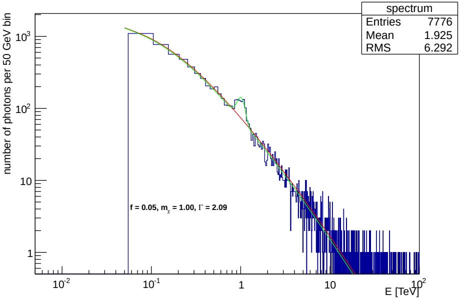
  - High energy cut-off ignored (may be included later)
- Likelihood is maximised using ROOT/MINUIT

Profile likelihood analysis

- Test statistic

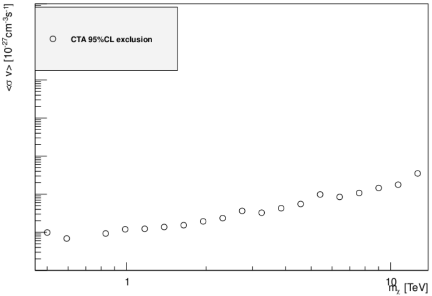
$$t_f = -2 \ln \frac{L(f = 0, m_\chi = 0, \Gamma)}{L(f, m_\chi, \Gamma)}$$

- The set of photons with energies $\{E\}$ is generated randomly from a distribution given by the likelihood function in previous slide
  - f and m_χ is varied to find 95%CL exclusion limit
  - number of generated photons is such that the background contribution matches the expectation by the MAGIC measurement



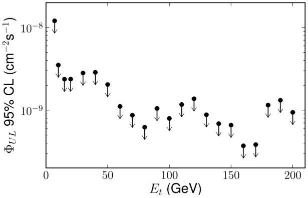
Results

- Results shown is for *one* proposed array layout, and assuming NFW dark matter profile
  - Sorry, no scale on the y-axis — waiting for cross checks and CTA approval
- Large improvement in sensitivity compared to present observatories



Results from Fermi-LAT

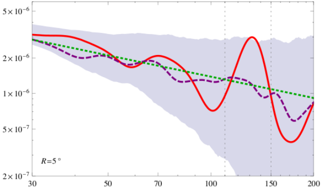
- Official Fermi-LAT results report only a upper limit on the flux due to dark matter annihilation[a]



[a] http://arxiv.org/abs/1205.2739

Results from Fermi-LAT

- Official Fermi-LAT results report only a upper limit on the flux due to dark matter annihilation[a]
- Two non-Fermi-LAT analyses using Fermi-LAT data report evidence for an excess around 130 GeV[b,c]
  - Frist analysis focus on galactic centre region
  - Second analysis focus on 6 galaxy clusters



[a] http://arxiv.org/abs/1205.2739
[b] http://arxiv.org/abs/1203.1312
[c] http://arxiv.org/abs/1207.4466

Outlook

- Near future developments
  - Study sensitivity to different DM profiles (T Buanes)
  - Compare different proposed array layouts (T Buanes)
  - Include $\chi\chi \to \gamma Z$ contribution (T Buanes, Ø Dale)
  - Include high energy cut-off (T Buanes, Ø Dale)
  - Generalise code to be able to use other observational input, e.g. Fermi-LAT (T Buanes, K Morå)
- Longer term plans
  - Optimisation of galactic centre target region
  - Other target regions