# Indirect dark matter detection

## Using Gamma-ray telescopes

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# Outline

# Introduction

- Indirect detection via $\gamma$-rays
- Annihilation to standard model particles
- $\chi\chi \rightarrow b\bar{b} \rightarrow \gamma\gamma...$
- $\chi\chi \rightarrow \tau^{+}\tau^{-} \rightarrow \gamma\gamma...$
- DM map of the Universe

# Outline

# Theoretical *gamma*-ray flux

$$I_\gamma(E,\Theta) = \frac{1}{2}\frac{\langle\sigma v\rangle}{m_{DM}^2}\frac{dN_{\gamma,ann}}{dE_\gamma}\frac{1}{4\pi}\int dl \rho_{DM}^2(r[l,\Theta])$$

- Particle physics factor
- Astrophysics factor

# Outline

# Particle physics factor

$$\frac{1}{2}\frac{\langle \sigma v \rangle}{m_{DM}^2}\frac{dN_{\gamma,ann}}{dE_\gamma}$$

Relic abundance $\sim$ annihilation rate:

$$\Omega_{DM} h^2 \sim \frac{3 \times 10^{-27} cm^3 s^{-1}}{\langle \sigma v \rangle}$$

Which implies:

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} cm^3 s^{-1}$$

# Particle physics factor

$$\frac{1}{2}\frac{\langle \sigma v\rangle}{m_{DM}^2}\frac{dN_{\gamma,ann}}{dE_\gamma}$$

Differential spectrum of emitted gamma-rays:

$$\frac{dN_{\gamma,ann}}{dE_\gamma}$$

Can be written as:

$$\frac{dN_{\gamma,ann}}{dE_\gamma} = \sum_i B_i \frac{dN^i_{\gamma,ann}}{dE_\gamma}$$

# Particle physics factor

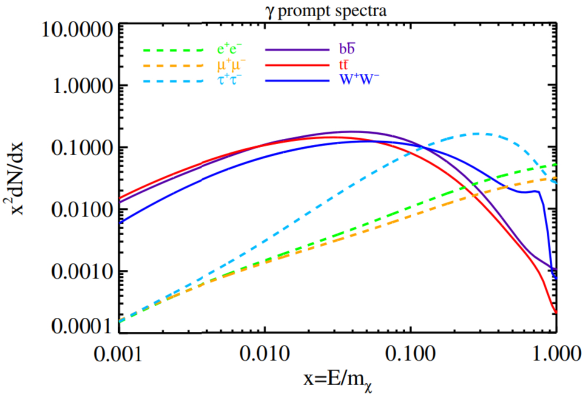



Figure: Figure from Gaskins et al. 2016: Gamma-ray spectrum from dark matter ($m_{DM} = 500 GeV$) annihilation to six different final states, calculated using PPPC4DMID [1].

# Particle physics factor

$$\frac{1}{2}\frac{\langle \sigma v \rangle}{m_{DM}^2}\frac{dN_{\gamma,ann}}{dE_\gamma}$$

- Factor $\frac{1}{2}$ due to being its own anti particle.
- Factor $1/m_{DM}^2$ cancels the density squared integral.

# Outline

# Astrophysical factor

$$\frac{1}{4\pi}\int dl\rho^2_{DM}(r[l,\Theta])$$

J-factor definition:

$$J = \frac{1}{\Delta\Omega}\int\int_{\Delta\Omega}\rho^2_{DM}(l,\Omega)dld\Omega$$

Normalization factor:

$$\int d\Omega = \int_0^{2\pi}\int_0^{\pi}\sin\theta d\theta d\phi = 4\pi$$

# Astrophysical factor

Simple density function:

$$\rho_{NFW} = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left[1 + \left(\frac{r}{r_s}\right)\right]^2}$$

- R dependence
- Relate to line of sight integral

# Astrophysical factor

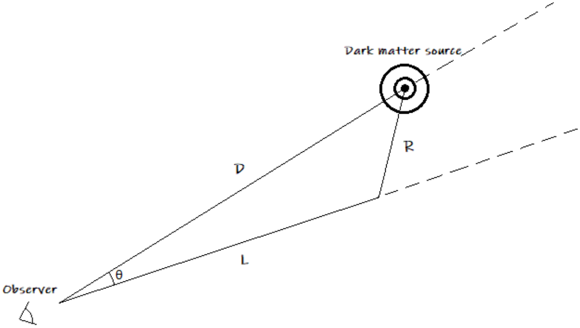



Figure: Top down view of observer looking down the line of sight with some angular separation Θ at a dark matter source.

- $R = \sqrt{L^2 + D^2 - 2L\cos\Theta}$

# Outline

# Theoretical *gamma*-ray flux - look back

$$I_\gamma(E,\Theta) = \frac{1}{2}\frac{\langle \sigma v\rangle}{m_{DM}^2}\frac{dN_{\gamma,ann}}{dE_\gamma}\frac{1}{4\pi}\int dl \rho_{DM}^2(r[l,\Theta])$$

- Rate of annihilation per volume: $\frac{1}{2}\frac{\langle \sigma v\rangle \rho_{DM}^2}{m_{DM}^2}$
- Differential spectrum of emitted gamma-rays: $\frac{dN_{\gamma,ann}}{dE_\gamma}$
- Volume: $\frac{1}{4\pi}\int dl$

# Sagittarius dwarf galaxy

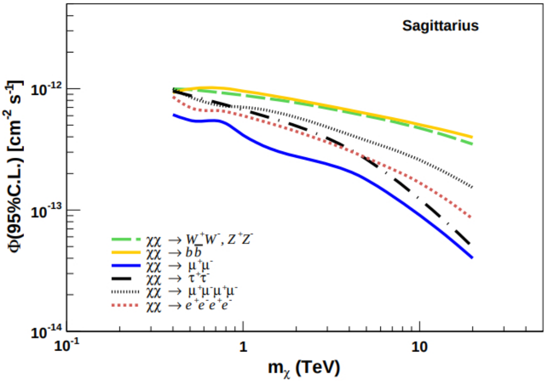



Figure: Figure from Abramowski et al. 2014: Gamma-ray flux as a function of dark matter mass ($m_\chi$) under different annihilation channels.

# Outline

# DM density profiles and observations

- What would DM-induced gamma-ray signals look like?
- Highly dependent on DM density profiles!
- Hard to constrain observationally
- Usually given as model input

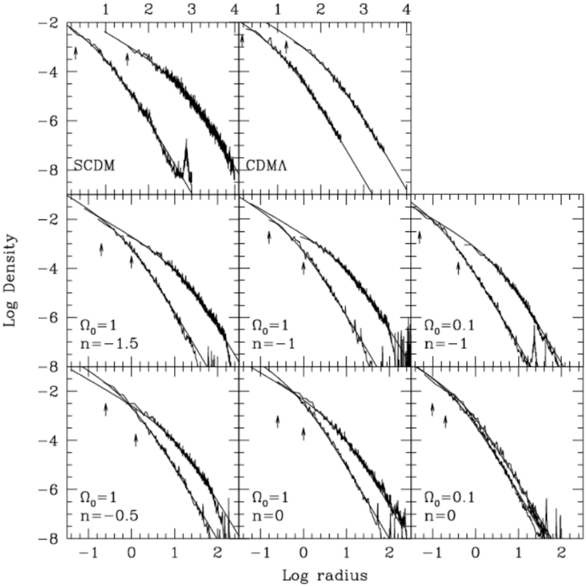
# The NFW profile

- Navarro, Frenk  White (1996)
- N-body simulation
- Showed that:

$$\rho_{NFW} = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)\right]^2} \tag{1}$$

can be used to fit DM haloes in arbitrary cosmology.

# The NFW profile




*Navarro et al. (1997)*

# The GNFW profile

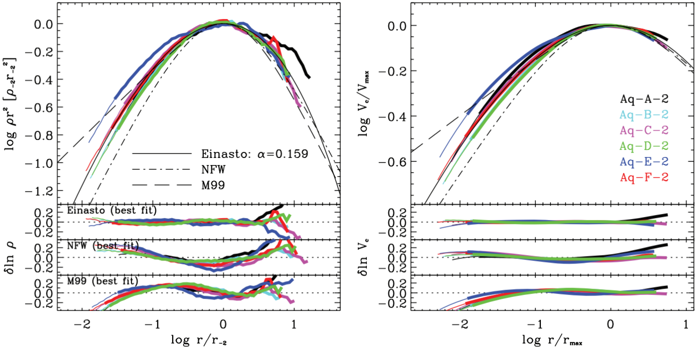
- Generalized version of the NFW profile
- Steeper slopes close to galactic center
  - Adiabatic compression
  - Supernovae and AGN feedback
- Arbitrary inner slope $\gamma$
- NFW for $\gamma = 1$

$$\rho_{GNFW} = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1 + \left(\frac{r}{r_s}\right)\right]^{3-\gamma}} \tag{2}$$

# The Einasto profile

- Systematic discrepancy between NFW and N-body
- Radius-dependent slope

$$\rho_{Ein}(r) = \rho_0 \exp -\frac{2}{a}\left[\left(\frac{r}{r_s}\right)^a - 1\right] \tag{3}$$




*Navarro et al. (2010)*

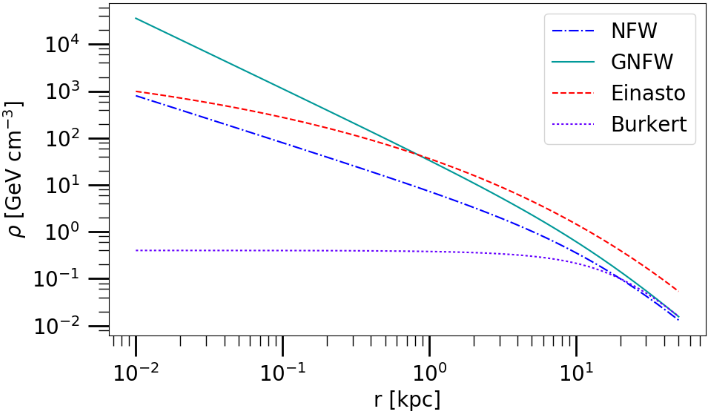
# The Burkert profile

- Problem: spheroidal dwarf galaxies (dSphs)
  - Low density
  - Homogeneous
- Flattens towards the center

$$\rho_{Burk}(r) = \frac{\rho_0}{\left(1+\frac{r}{r_s}\right)\left(1+\left(\frac{r}{r_s}\right)^2\right)} \qquad (4)$$

*ESO/Digital Sky Survey 2*

# Comparison



NFW
GNFW
Einasto
Burkert
$\rho$ [GeV cm$^{-3}$]
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
r [kpc]

# Outline

# Some questions

- Do observed $\gamma$-rays accurately reflect the DM density?
- Scattering processes?
- Background sources?

# Compton scattering

- Optical depth?
- Assuming $n_e \approx 10^0\ \mathrm{cm}^{-3}$ (typical for ISM)
- Thomson approximation $\sigma_{K-N} \leq \sigma_{Th} \approx 10^{-24}$ cm
- Max distance $d$ 20 kpc $\approx 10^{22}$ cm
- $\tau \approx n_e \sigma_{Th} d \approx 10^{-5}$
- $\longrightarrow$ **of little consequence**

# Pair production

- annihilation of two photons into particle-antiparticle

$$\gamma\gamma \longrightarrow e^+ e^- \tag{5}$$

- Suppose a DM-induced photon annihilates with a CMB photon. What energy should the photon minimally have for pair production?

# Pair production

- annihilation of two photons into particle-antiparticle

$$\gamma\gamma \longrightarrow e^{+}e^{-} \tag{6}$$

- Suppose a DM-induced photon annihilates with a CMB photon. What energy should the photon minimally have for pair production?
- $E_{\gamma} \geq 10^{14}$ eV
- Of litte consequence to Fermi-LAT
- Possibly important for CTA

# Constraints from Fermi-LAT (2017)

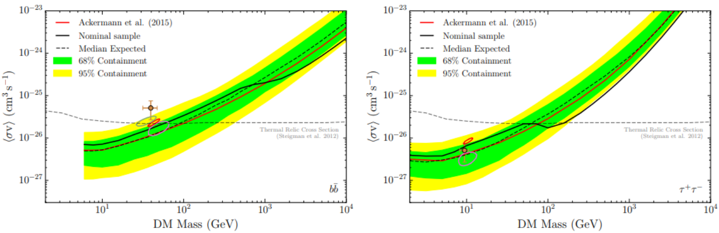



Figure: [2]

# Future telescopes - CTA

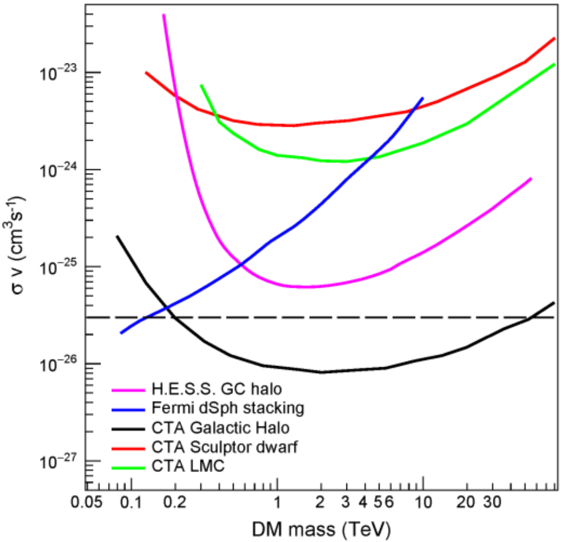



Figure: [3]

# Telescopes



Table: [4], [2], [5], [6] , [7], [8], [3], [9], [10], [11], [12]

| Name | Energy range | $\sigma v$ $(cm^3/s)$ |
|---|---|---|
| Fermi-LAT | 20 MeV - 300 GeV | $\sim 4 \cdot 10^{-26}$ |
| H.E.S.S | 300 GeV - 70 TeV | $4 \cdot 10^{-28}$ |
| Veritas | 85 GeV - 30 TeV | $2.85 \cdot 10^{-24}$ |
| Magic | 100 GeV - 100 TeV | $3.8 \cdot 10^{-24}$ |
| HAWC | 500 GeV - 100 TeV | $\sim 10^{-24}$ |
| CTA | 100 GeV - 10 TeV | $5 \cdot 10^{-27} - 3 \cdot 10^{-26}$ |
| CALET | 100 GeV - 1 TeV | — |
| GAMMA400 | 20 MeV - 1 TeV | — |
| HERD | 10 GeV - 1 TeV | $6 \cdot 10^{-30} - 5 \cdot 10^{-29}$<br>$4 \cdot 10^{-27} - 9 \cdot 10^{-27}$ |

# For Further Reading I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