Dark Matter searches in WLM dwarf galaxy

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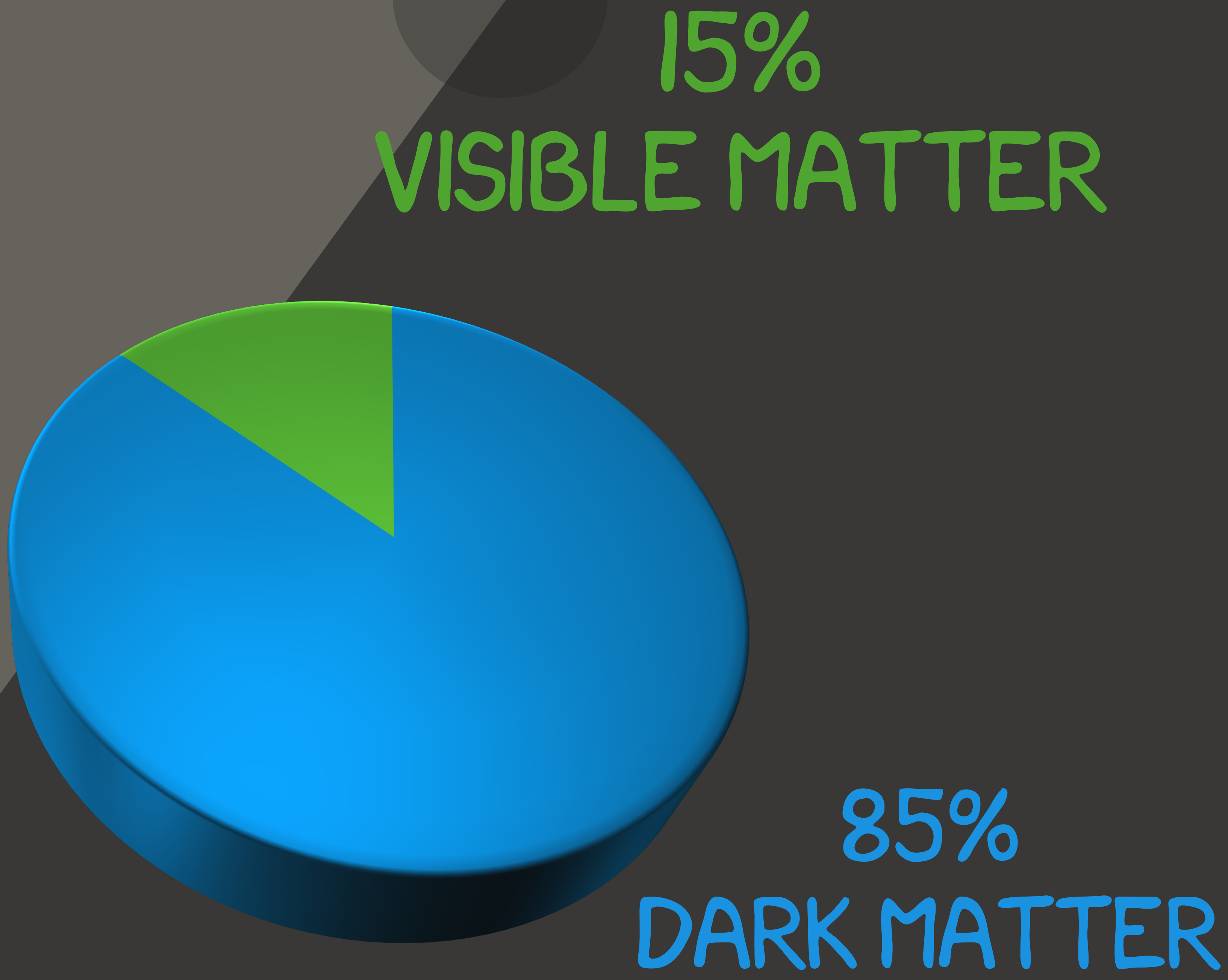
OUTLINE

- Dark matter indirect detection
- Properties and theoretical aspects
- Observations & Data analysis
- Upper limits
- Conclusion

PART 1

Dark matter indirect detection

DARK MATTER



OBSERVATIONAL EVIDENCE

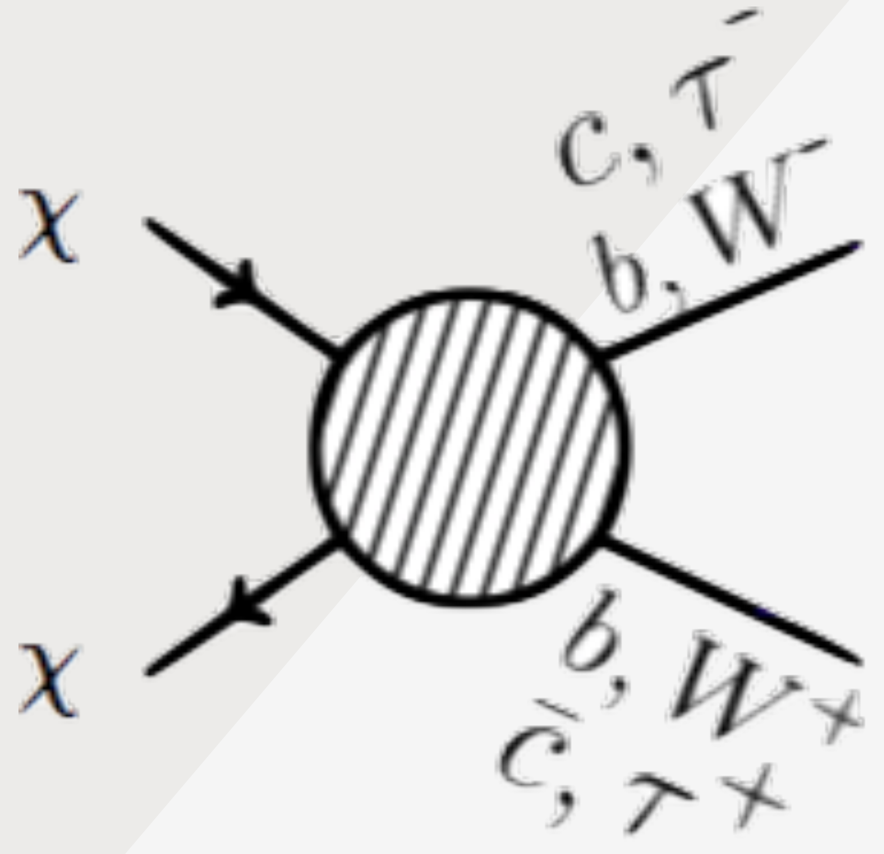
- Dynamics within the galaxies and clusters
- Gravitational lensing
- Cosmic Microwave Background anisotropies

WIMP *(Weakly Interacting Massive Particle)*

- Massive
- Neutral
- Stable

Indirect Detection

Annihilation of dark matter (DM) particles → **Particles of Standard Model (bosons, quarks, leptons)**



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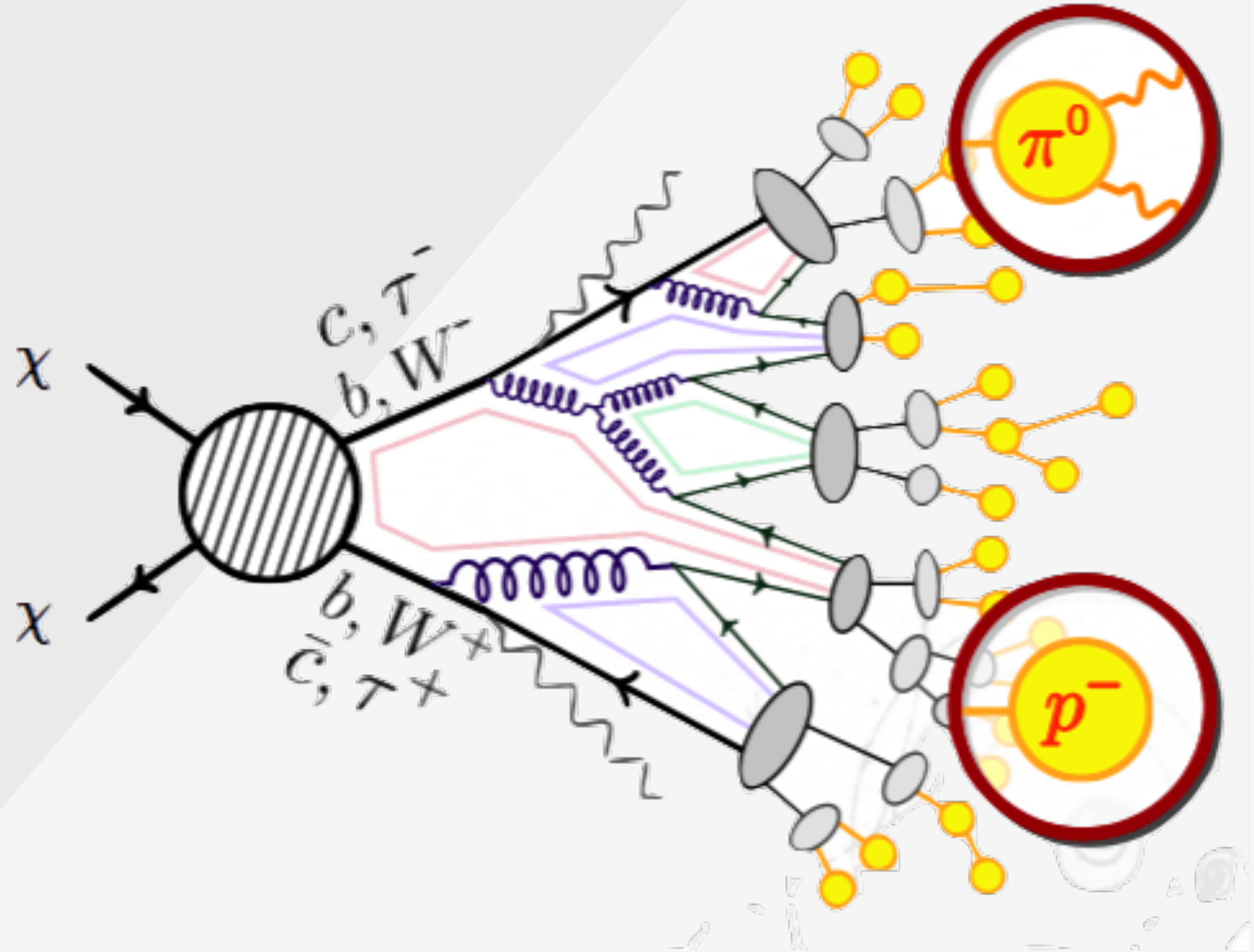


Observable flux of particles

- Positrons/electrons
- Neutrinos
- Antiprotons, antideuteriums
- **γ rays**

γ rays

- **High** energies (~GeV-TeV)
- **Neutral** particles
- Not **deflected** by the magnetic field of the Galaxy
- **Slight attenuation only** at Galaxy scale

→ **Localization** of their origin

γ-ray flux

γ-ray flux DM (E, θ) = Normalisation x Spectrum x Morphology

γ-ray flux

J factor
DM density squared
integrated over the
line-of-sight and the
solid angle

γ-ray flux DM = Normalisation x Spectrum x Morphology
(E, θ)

γ-ray flux

γ-ray flux DM (E, θ) = Normalisation x Spectrum x Morphology

J factor

DM density squared

integrated over the line-of-sight and the solid angle

Number of **γ per annihilation and per energy range** for a given DM mass m_χ

γ-ray flux

Contains the **DM annihilation cross-section $\langle\sigma v\rangle$** and the **DM mass m_χ**

J factor

DM density squared

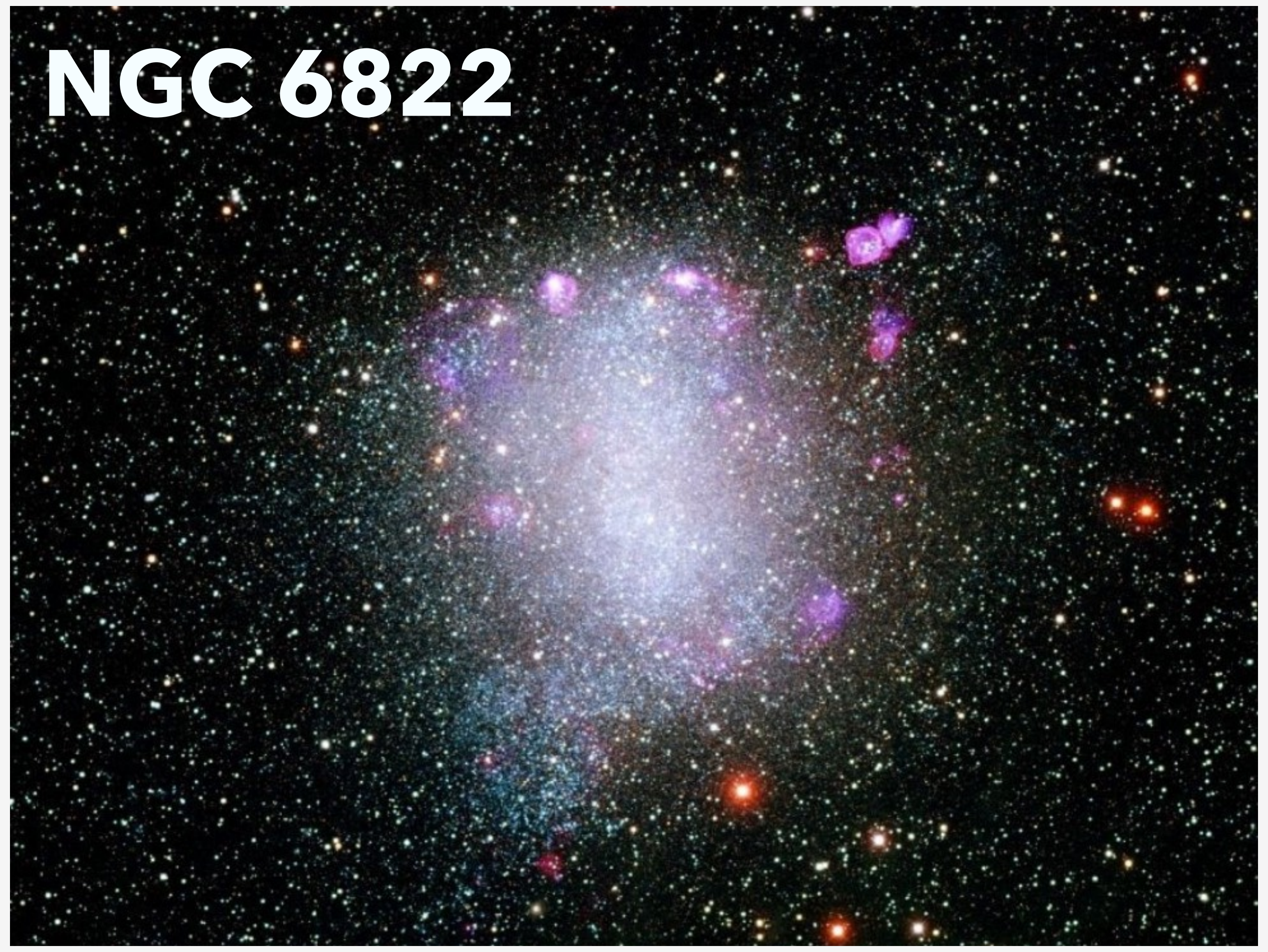
integrated over the line-of-sight and the solid angle

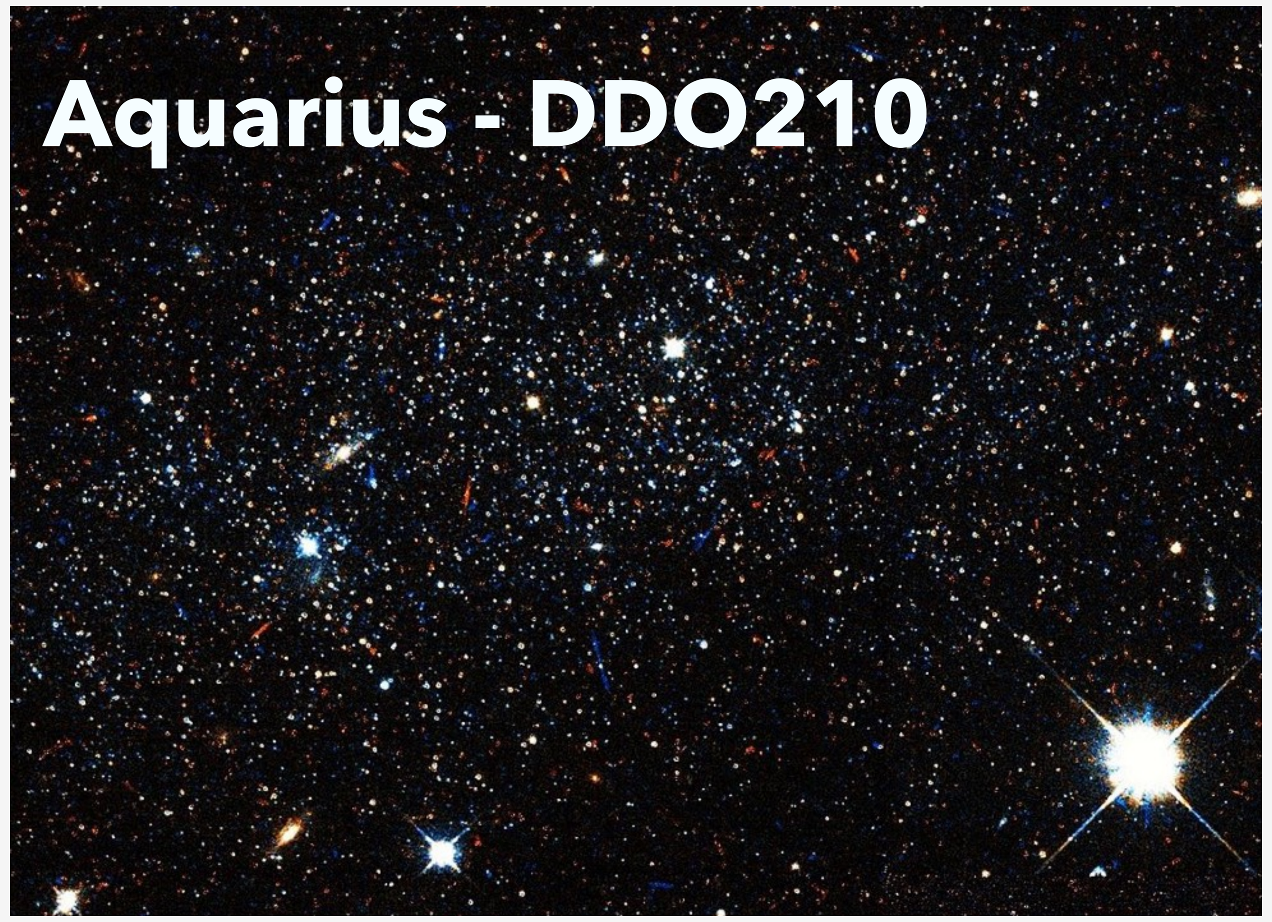
γ-ray flux DM (E, θ) = Normalisation x Spectrum x Morphology

Number of **γ per annihilation and per energy range** for a given DM mass m_χ

PART 2

Properties and theoretical aspects

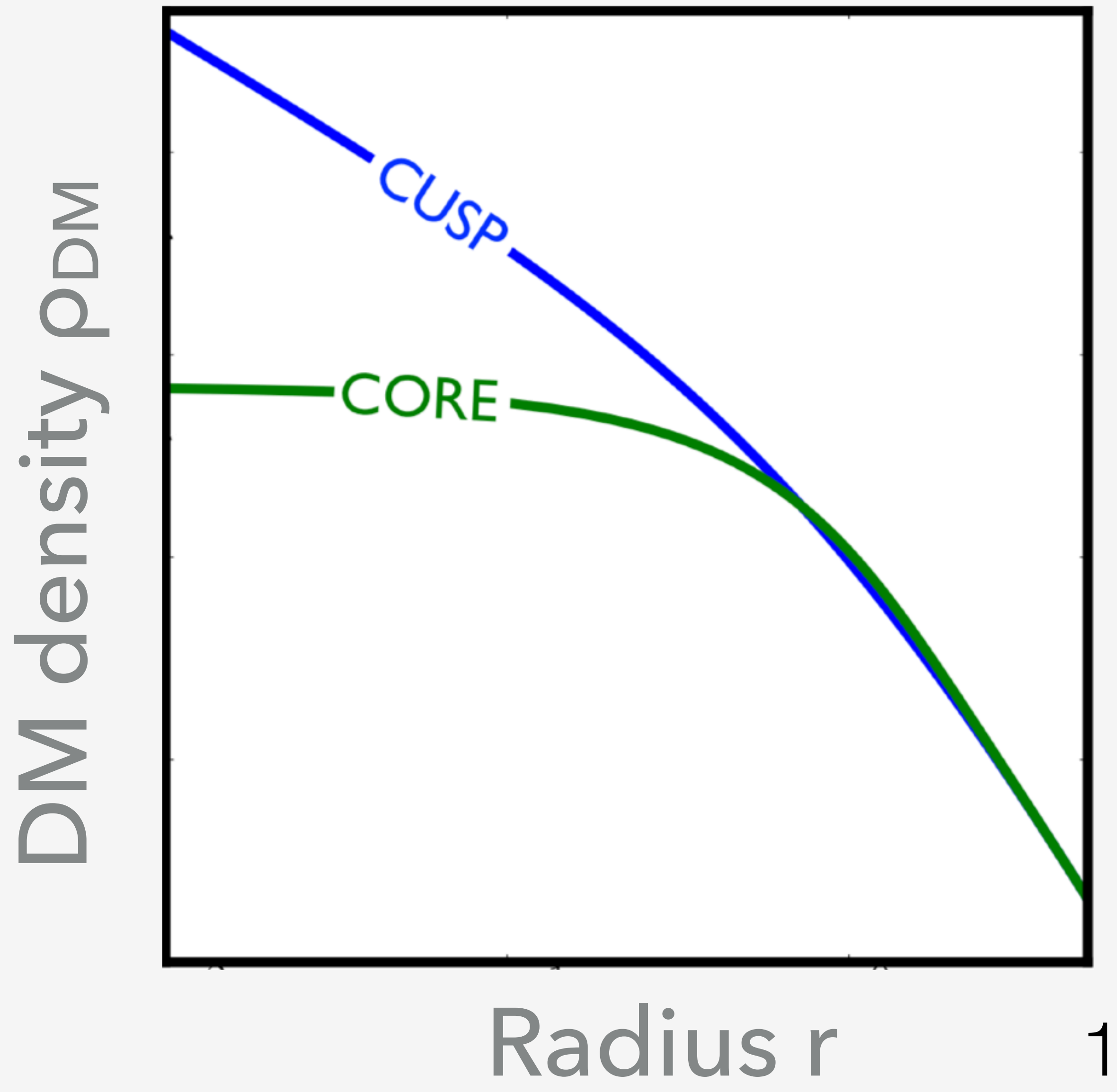




Dwarf irregular galaxies

Properties of the dwarf irregular galaxies (dIrrs)

- Rotation supported & simple kinematics
- DM dominated - J ~ 10^{16} - 10^{17} GeV^2.cm^{-5}
- Extended sources: 0.3°< θ_{halo}< 6°
- Tend to follow a cored profile
- Star-forming regions below 0.1°
  negligible signal for HESS

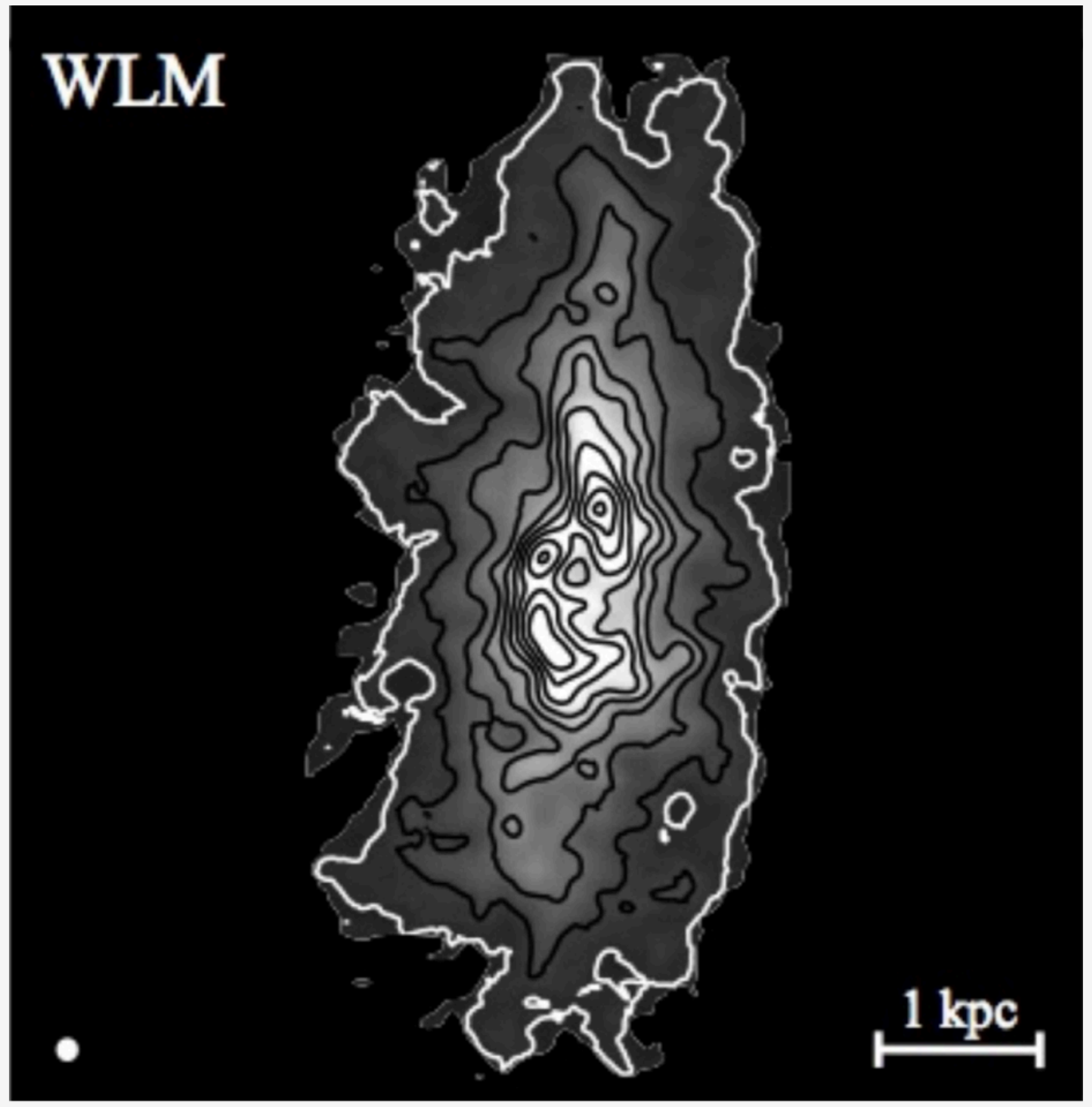


WLM dwarf galaxy

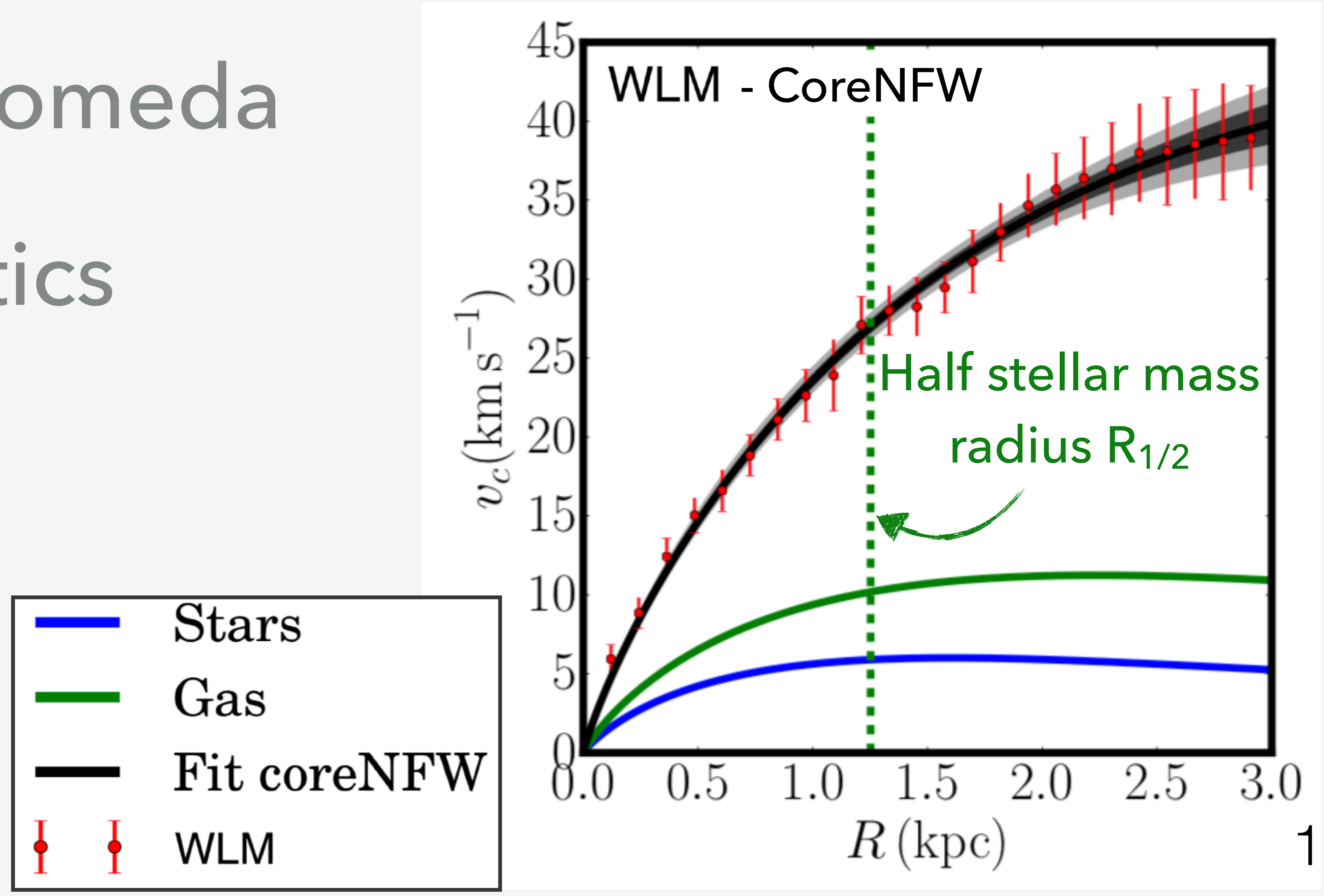
Properties of WLM

- **First** irregular dwarf **observed** by HESS and an IACT experiment
- **Isolated** source
- Located at ~ **1 Mpc** from the Milky Way and Andromeda
- **Excellent** HI data, photometry and stellar kinematics
- **Smooth** rotation curve
- Use of a new profile: **CoreNFW**

Smooth HI distribution



Smooth rotation curve

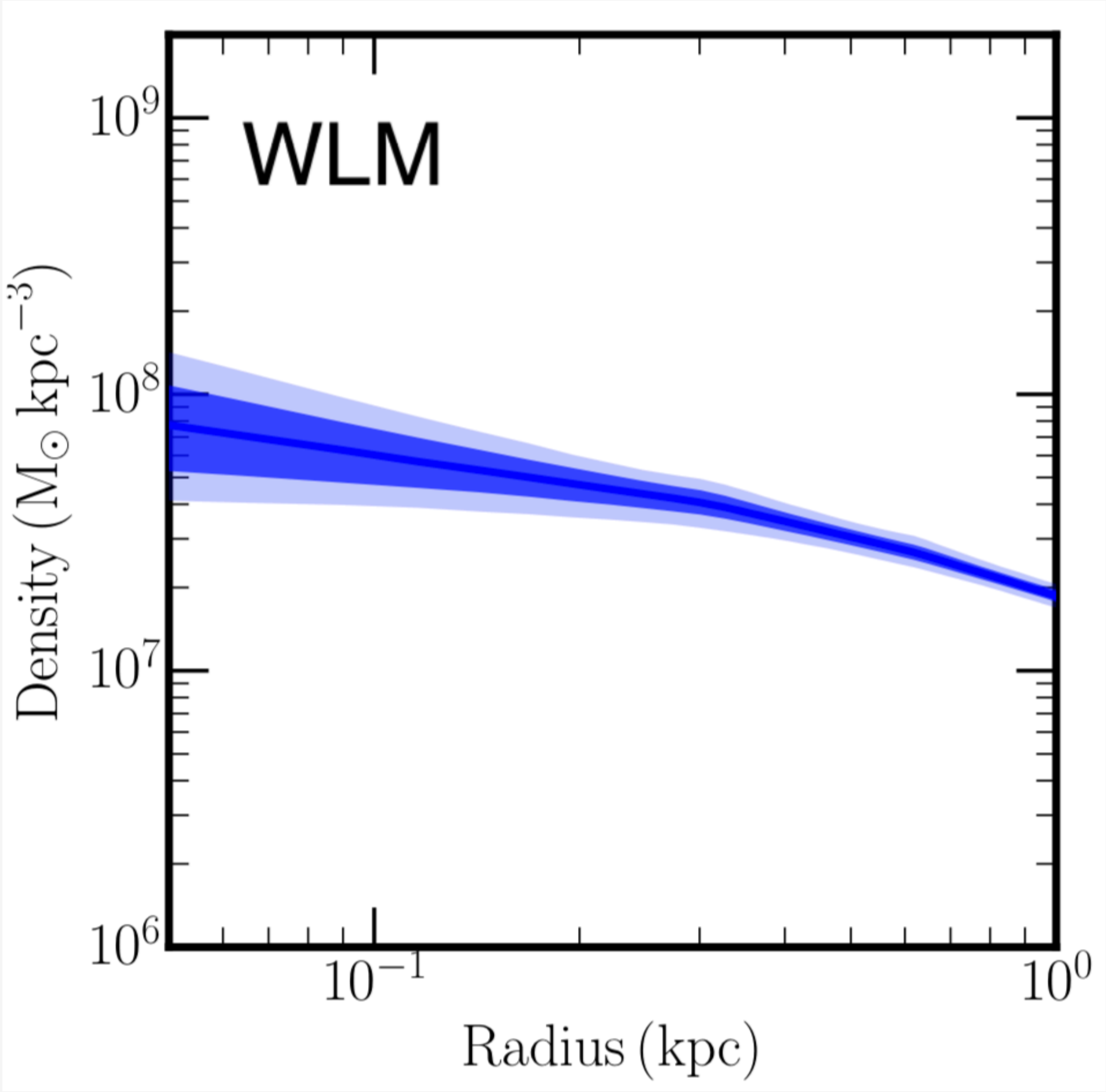


Ref: Read et al., 2016
MNRAS, Vol. 462, Issue 4, 11 Nov 2016

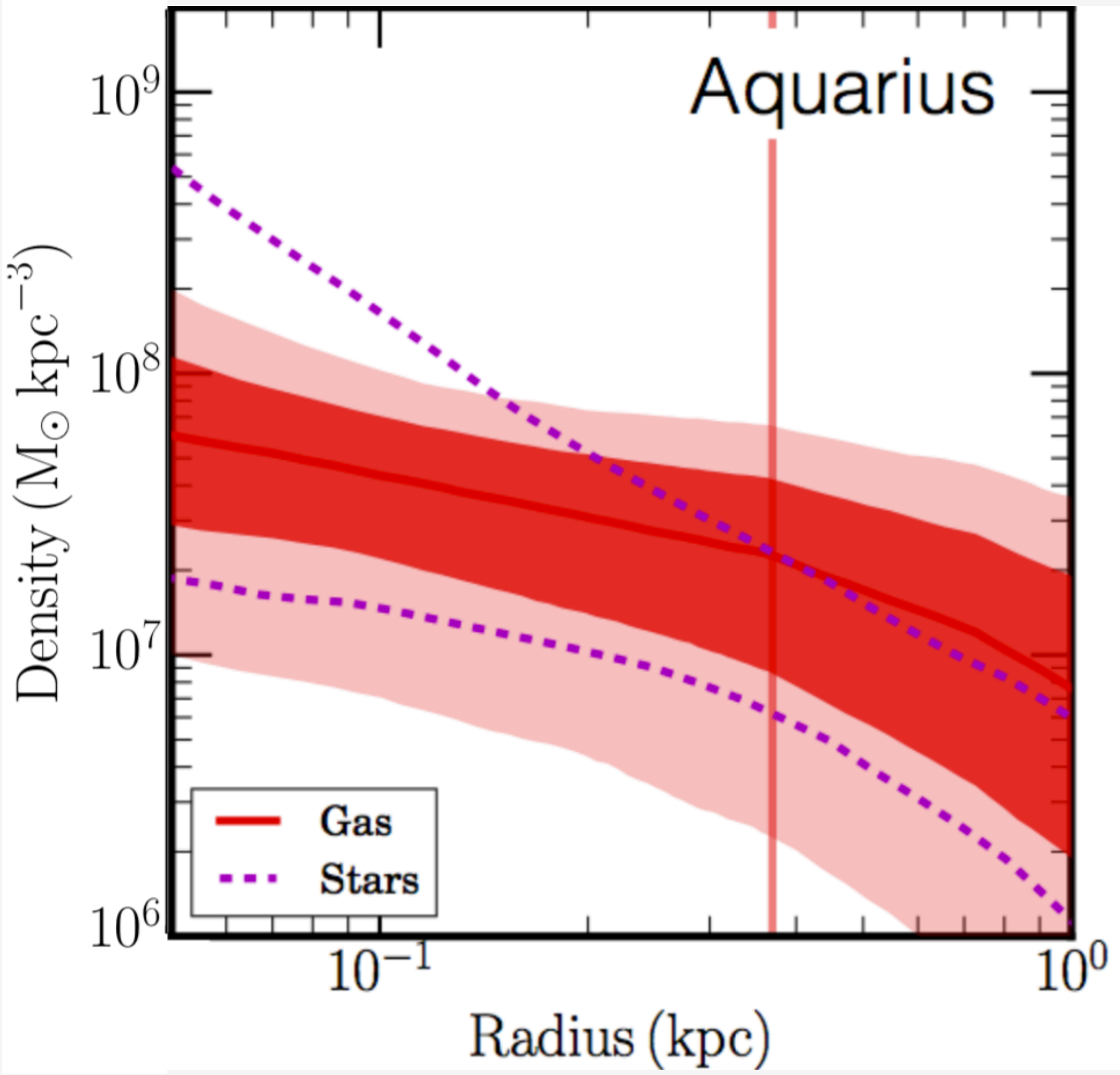
A new DM Profile: CoreNFW

Ref: Read et al., 2018
MNRAS, Vol. 484, Issue 1,
Mar 2019

CoreNFW - Takes into **account the history of the star formation** within the galaxy



VS



Mass profile
very well constrained
by the rotation curve

→

Very small uncertainties
on the DM profile

Mass profile
less constrained
by the rotation curve

→

Larger uncertainties
on the DM profile

A new DM Profile: CoreNFW

Ref: Read et al., 2018
MNRAS, Vol. 484, Issue 1,
Mar 2019

$$\rho_{\mathrm{coreNFW}}(r) = f^n \rho_{\mathrm{NFW}} + \frac{f^{n-1}(1-f^2)}{4\pi r^2 r_c} M_{\mathrm{NFW}}$$

DM component

$\rho_{NFW} = f(c_{200}, M_{200})$ NFW dark matter density profile

$M_{NFW}(<r) = g(c_{200}, M_{200})$ NFW dark matter cumulative mass profile

Concentration parameter

Virial mass

3 parameters

A new DM Profile: CoreNFW

Ref: Read et al., 2018
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Concentration parameter

Virial mass

Stellar component

$f^n = \left[\tanh\left(\frac{r}{r_c}\right)\right]^n$ generates a shallower density profile in the core of the galaxy

$r_c = \eta R_{1/2}$ core radius proportional to the half stellar mass radius

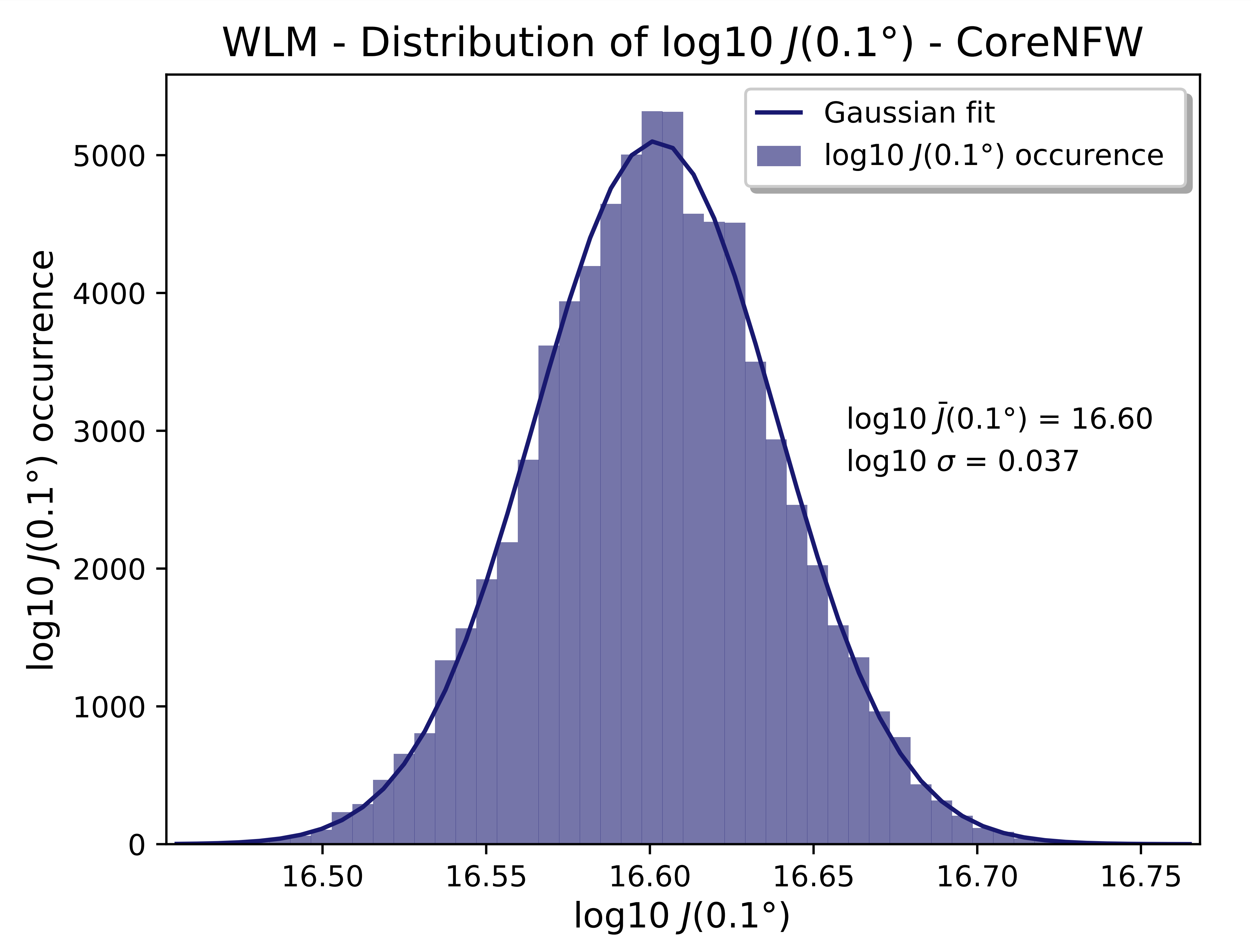
Coefficient

3 parameters

J Factor & uncertainties

J factor - Defines the **amount of dark matter annihilations** in a source

Histogram of J values



- Dataset (η, c_{200}, M_{200}) provided by Justin **Read**
- **Fit of the distribution**

Very small uncertainties on J

log10 J(0.1°) = **16.6 ± 0.037**

VS

Literature

log10 J(0.1°) = **16.63 ± 0.6**

Ref: Gammaldi et al, Phys. Rev. D 98, 083008

PART 3

Observations and data analysis

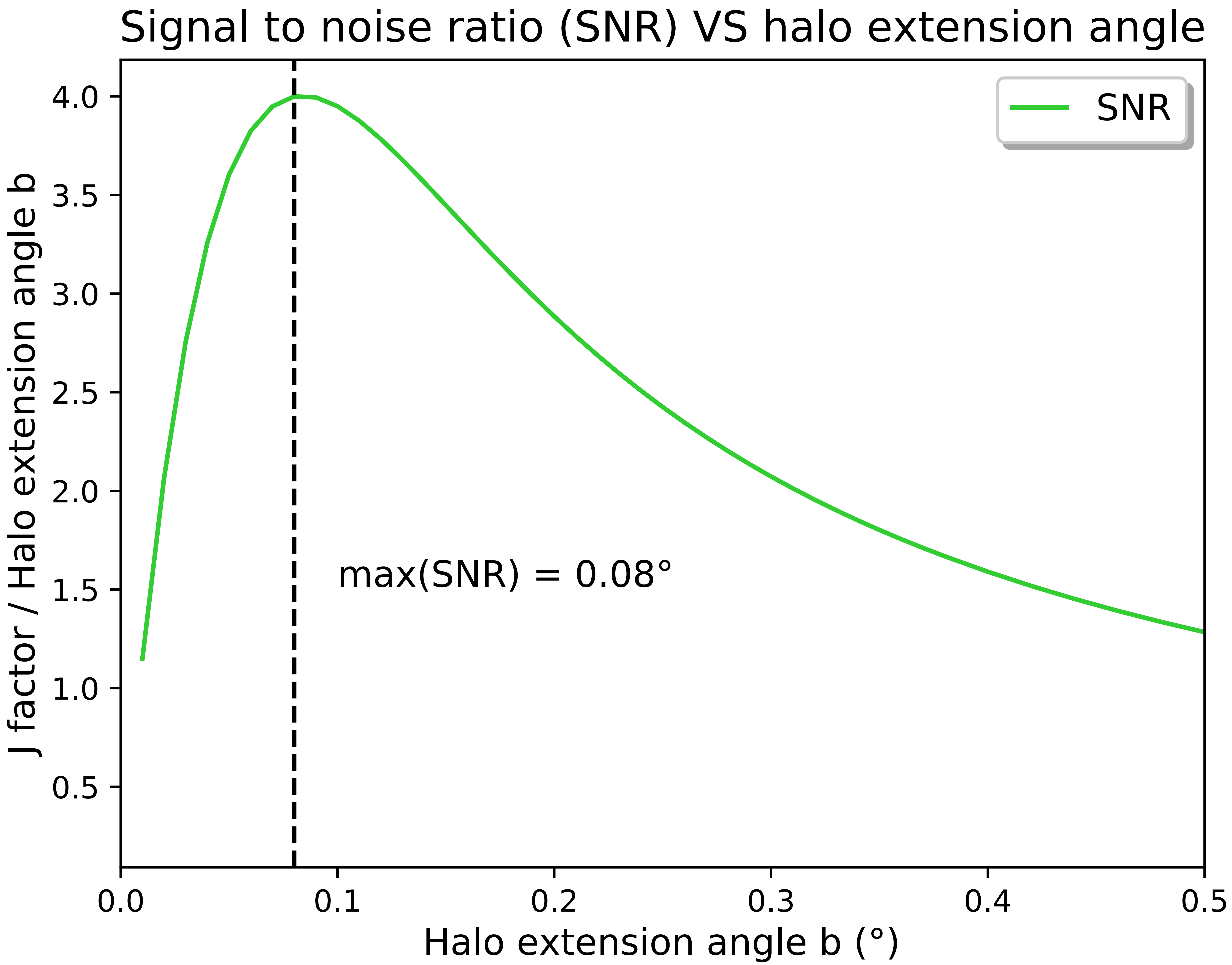
H.E.S.S.

The H.E.S.S. experiment

Array of 5 Cherenkov telescopes

- Located in **Namibia**
- Taking data since **2004**
- Detection of γ rays **~100 GeV à ~100 TeV**

Signal to Noise Ratio (SNR)



WLM as an **extended**

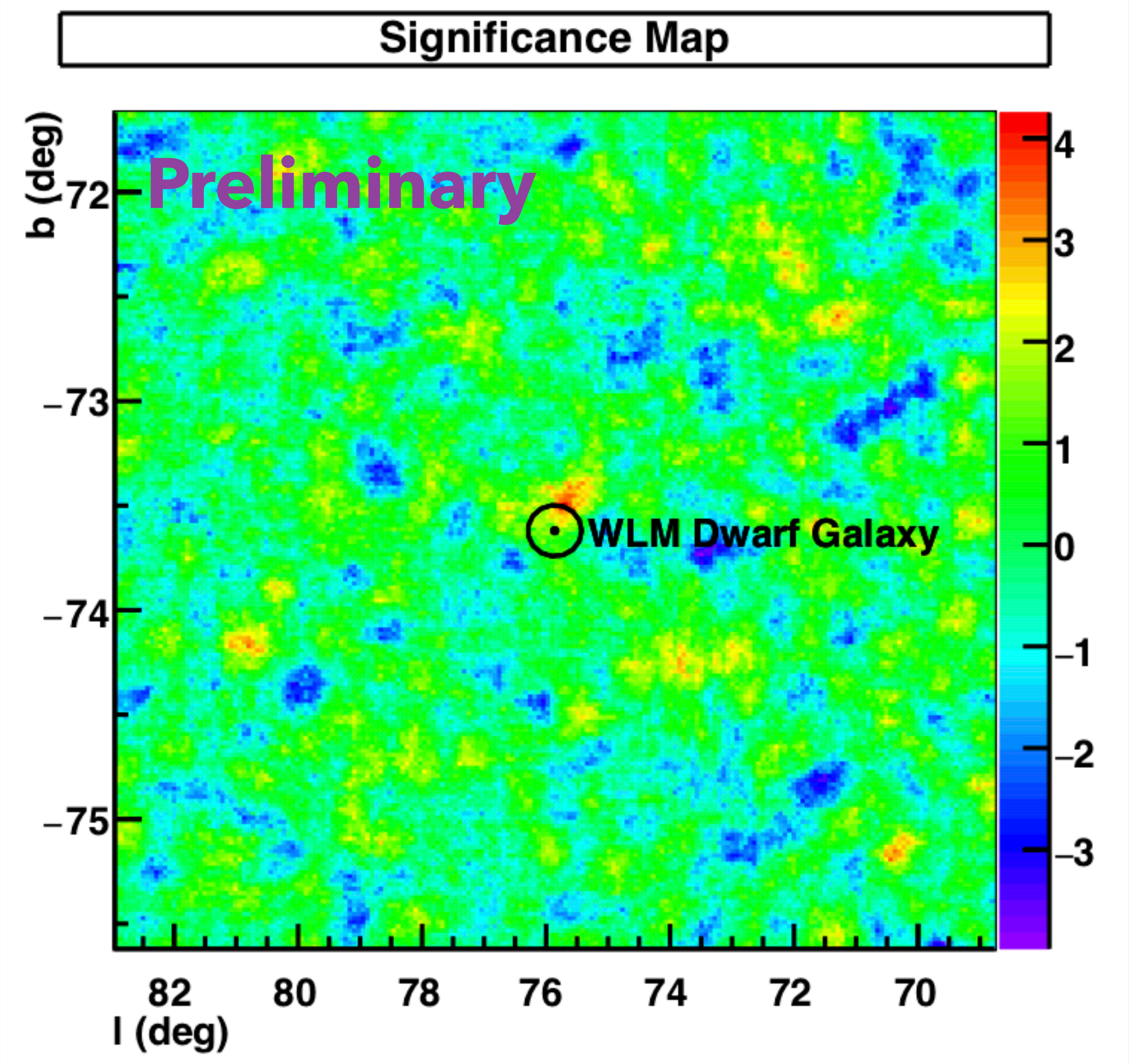
or

a **point-like** source?

Max(SNR) < 0.1°

→ WLM treated as a **point-like** source

Observation & Data Analysis



- **WLM** - Gal. coord. l = 75.86°, b = -73.62°
- Observations from **October to December, 2018**
- **~ 18** hours
- **No significant excess** in the FoV

Likelihood method and Test Statistic

Poisson likelihood for each energy bin:

$$\mathscr{L}_i^P = \frac{(N_{S_i} + N_{B_i})^{N_{ON_i}}}{N_{ON_i}!} \exp - (N_{S_i} + N_{B_i}) \cdot \frac{(\alpha N_{B_i})^{N_{OFF_i}}}{N_{OFF_i}!} \exp(-\alpha N_{B_i})$$

Gaussian likelihood to model the uncertainties on J:

$$\mathscr{L}^J = \frac{1}{\ln(10)\sqrt{2\pi}\sigma_J \bar{J}} \exp - \frac{(\log_{10} J - \log_{10} \bar{J})^2}{2\sigma_J^2}$$

Prescription of Fermi-LAT & MAGIC
Ref: JCAP 1602 (2016) 039

Likelihood ratio test statistics:

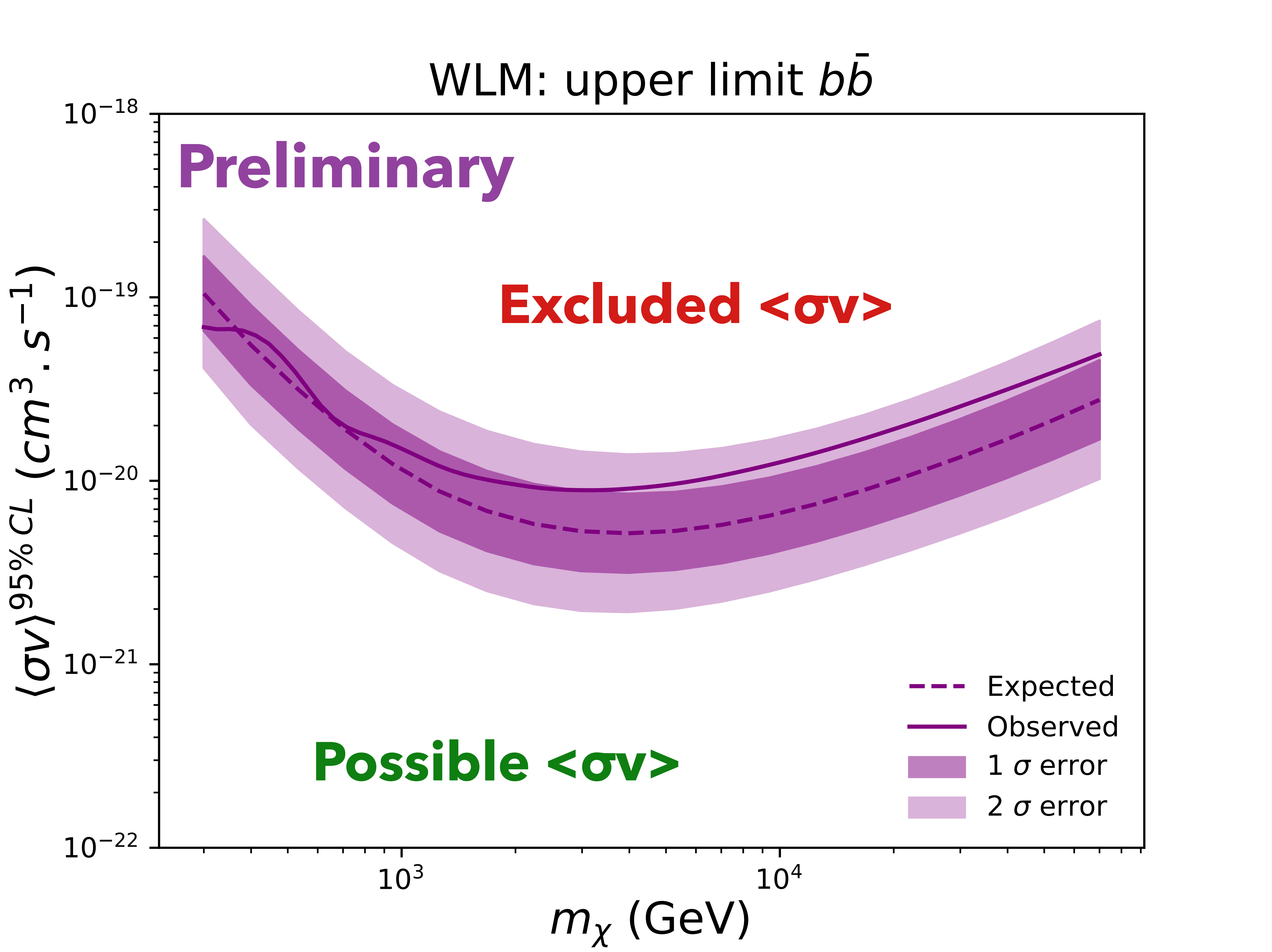
$$\Lambda = -2\ln\frac{\mathscr{L}_{H_0}}{\mathscr{L}_{H_1}} = -2\ln\frac{\mathscr{L}(N_{S_0}\,|\,\hat{N}_B, \hat{J})}{\mathscr{L}(\check{N}_S, \check{N}_B, \check{J})}$$

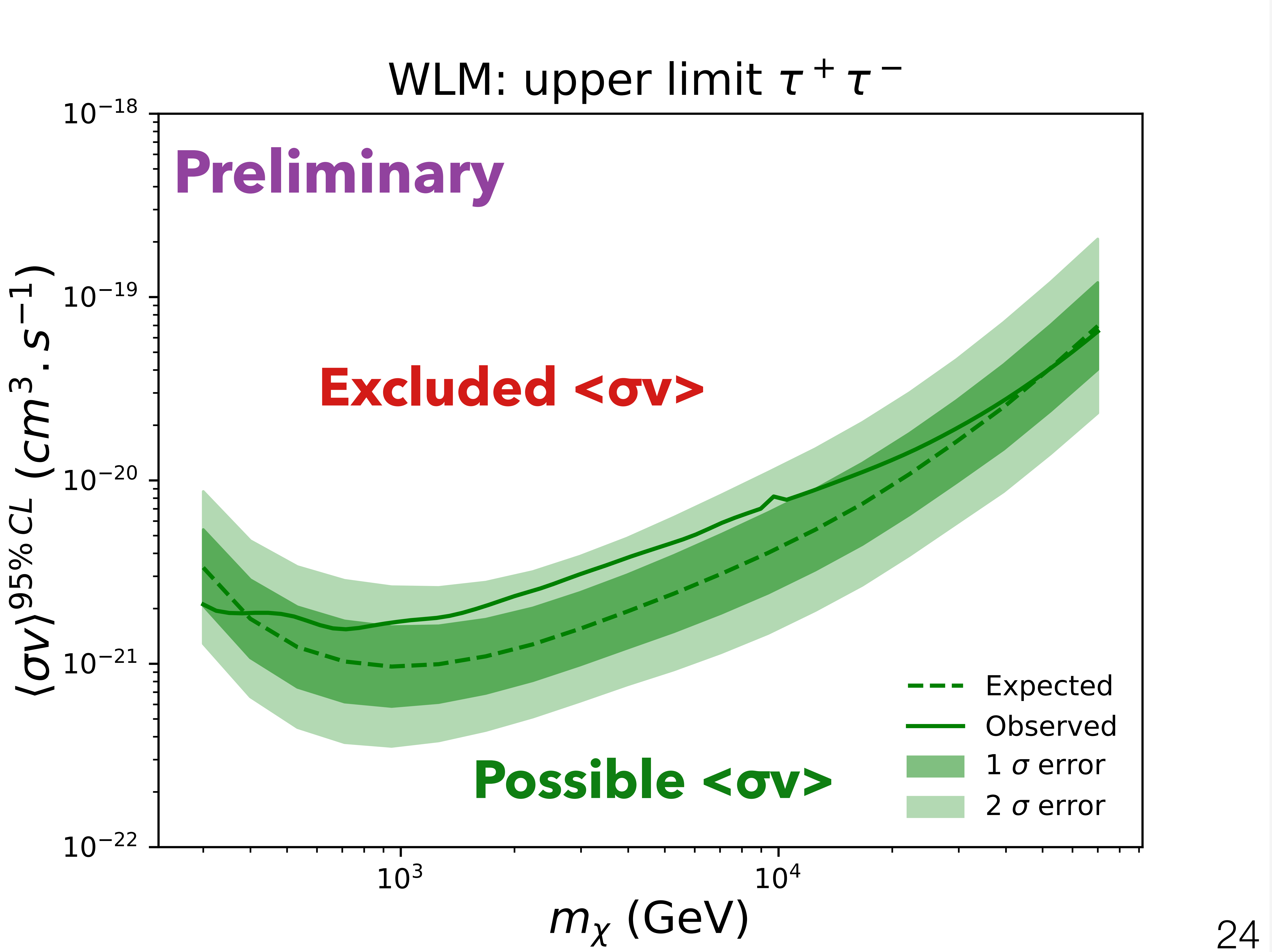
Ref: Cowan et al, 2010
Eur.Phys.J.C71:1554,2011

Upper Limits

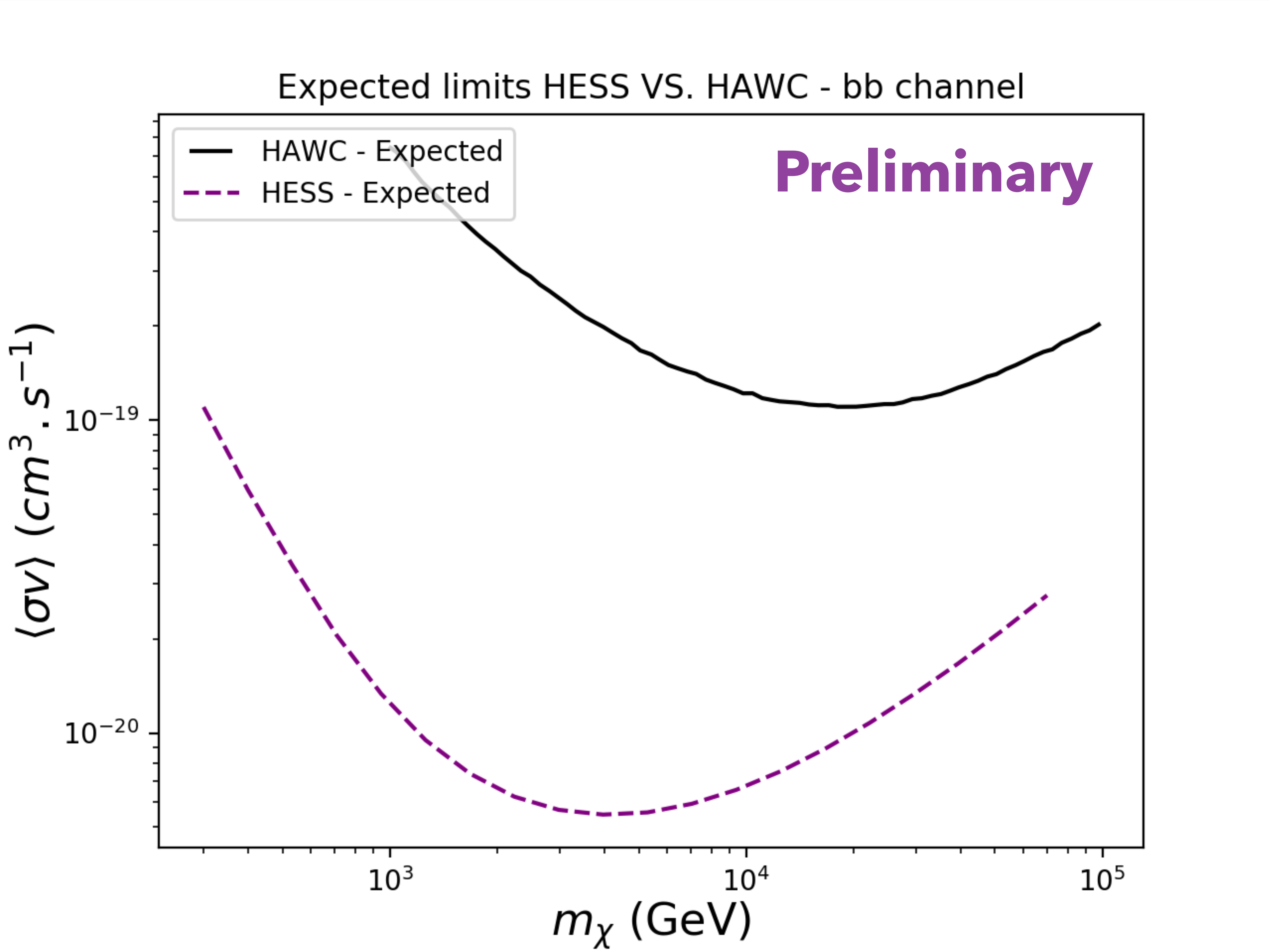
Expected and observed limits for 8 channels with J uncertainties

Example of upper limits for bb and WW channels





Comparison to HAWC's results



Ref: Gammaldi et al
Phys. Rev. D 98, 083008 (2018)

HAWC - UL for the whole object $\theta_{vir} = 2.6°$

VS

This work - UL for $\theta = 0.1°$

10x better than those published by HAWC

Conclusion

Conclusion

- **No excess** has been observed in the data
- **Upper limits** for 8 annihilation channels
- WLM as a **point-like** source
- **More competitive** than the upper limits set by HAWC

Papers & Conferences

- **Poster** presented at the **ICRC 2019**
- **Proceeding** on arXiV (arXiv:1908.10178)
- Talk accepted at **TeVPA 2019**
- Paper writing **in progress**

Backup

FLUX γ

$$\boxed{\Phi_\gamma(E_{\max}, E_{\min})} = \boxed{\int_{E_{\min}}^{E_{\max}} \frac{1}{2}\frac{\langle\sigma v\rangle}{4\pi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} dE_\gamma} \boxed{\int_{\Delta\Omega(\alpha,\phi)} d\Omega \int_{\text{los}} ds\, \rho_{\text{DM}}^2(r(s,\alpha_{\text{int}}))}$$

Flux γ
théorique

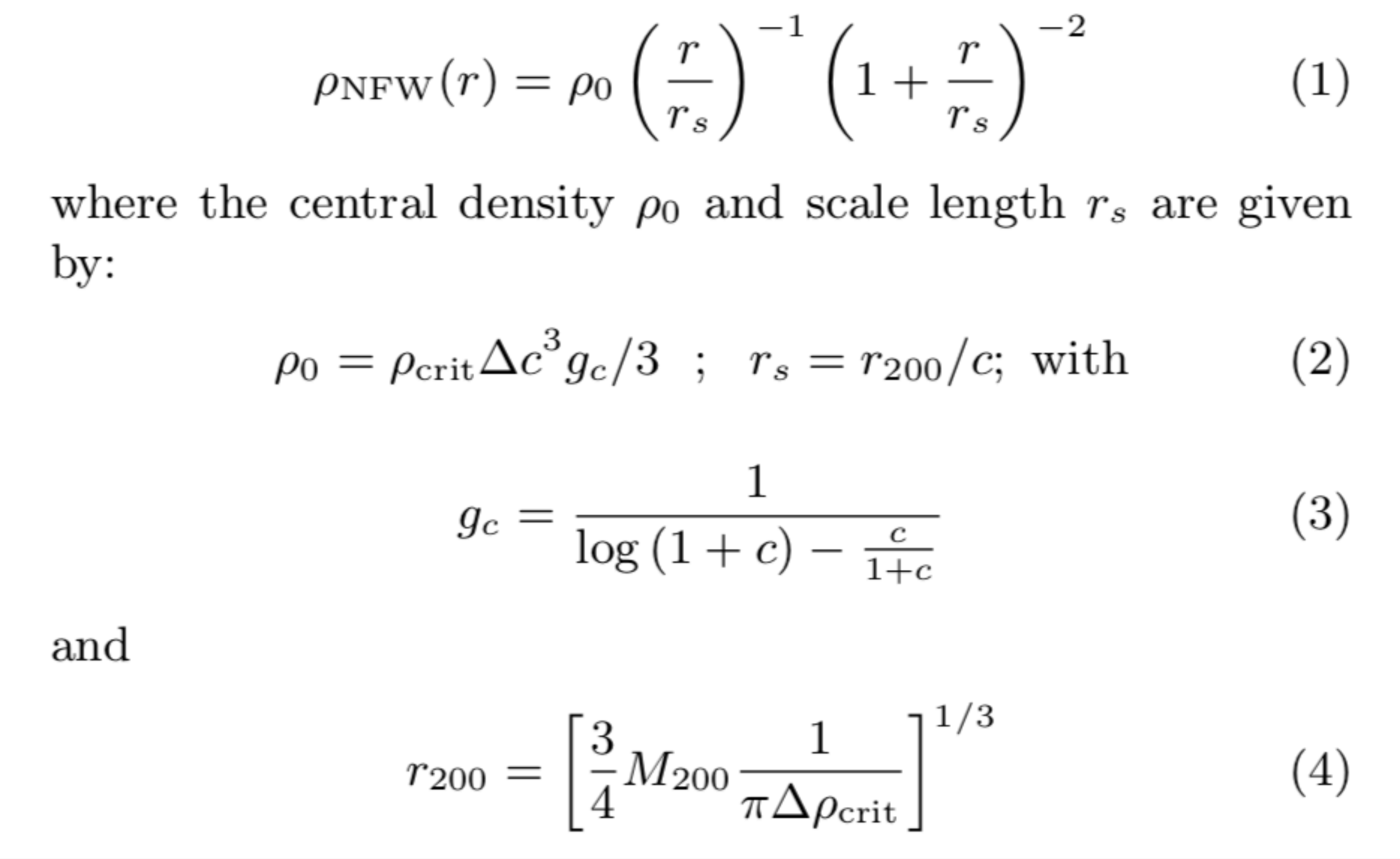
Facteur Φ_{PP}
Physique des particules

Facteur J
Astrophysique

- $\langle\sigma v\rangle$ Section efficace d’annihilation moyennée sur la distribution des vitesses
- $\frac{dN_\gamma^f}{dE_\gamma}$ Nombre de γ par annihilation et par intervalle d’énergie
- B_f Rapport de branchement - Hypothèse: 100% pour chaque voie d’annihilation
- ρ_{DM} Densité de matière noire (DM)
- m_χ Masse des WIMPs

NFW Profile

DM component - NFW profile



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

where the central density ρ_0 and scale length r_s are given by:

$$\rho_0 = \rho_{\mathrm{crit}} \Delta c^3 g_c / 3 \quad ; \quad r_s = r_{200}/c; \text{ with} \tag{2}$$

$$g_c = \frac{1}{\log(1+c) - \frac{c}{1+c}} \tag{3}$$

and

$$r_{200} = \left[\frac{3}{4} M_{200} \frac{1}{\pi \Delta \rho_{\mathrm{crit}}}\right]^{1/3} \tag{4}$$

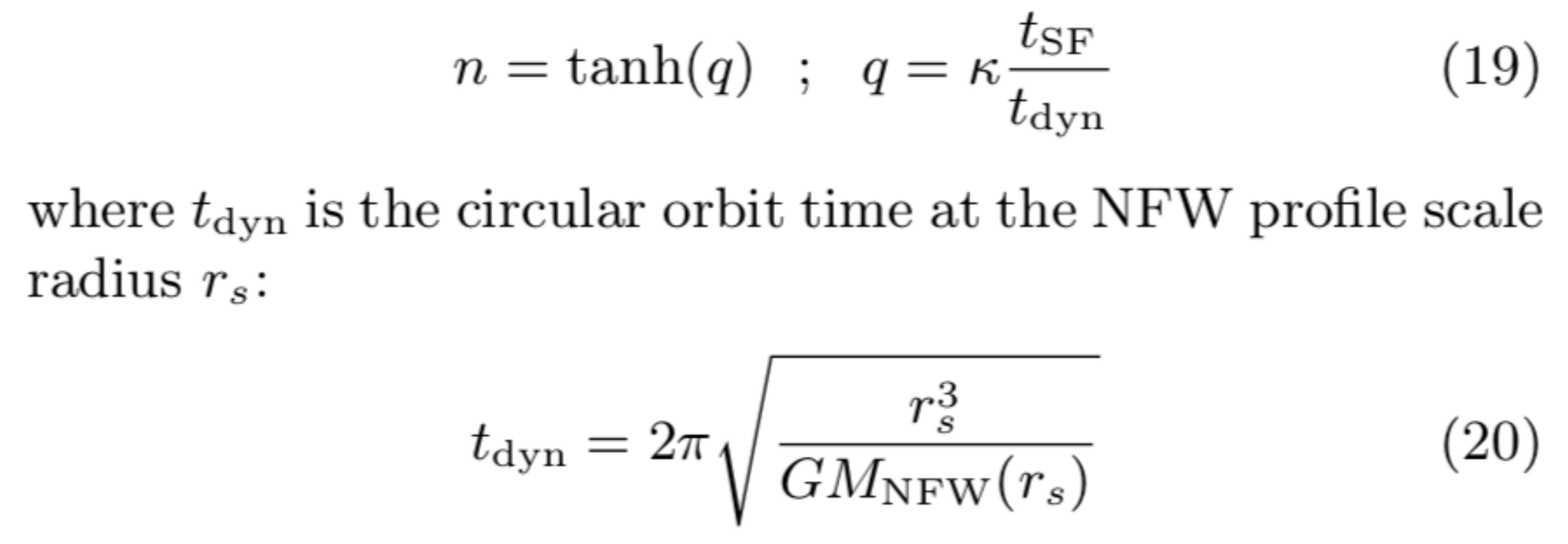
CoreNFW Profile

Stellar component

$$\rho_{\mathrm{coreNFW}}(r) = f^n \rho_{\mathrm{NFW}} + \frac{f^{n-1}(1-f^2)}{4\pi r^2 r_c} M_{\mathrm{NFW}}$$

n = how shallow the core becomes
(n=0 full cusp, n=1 full core)

$$f^n = \left[\tanh\left(\frac{r}{r_c}\right)\right]^n$$



$$n = \tanh(q) \quad ; \quad q = \kappa \frac{t_{\mathrm{SF}}}{t_{\mathrm{dyn}}} \tag{19}$$

where t_{dyn} is the circular orbit time at the NFW profile scale radius r_s:

$$t_{\mathrm{dyn}} = 2\pi \sqrt{\frac{r_s^3}{G M_{\mathrm{NFW}}(r_s)}} \tag{20}$$

$$r_c = \eta R_{1/2}$$

Half stellar mass

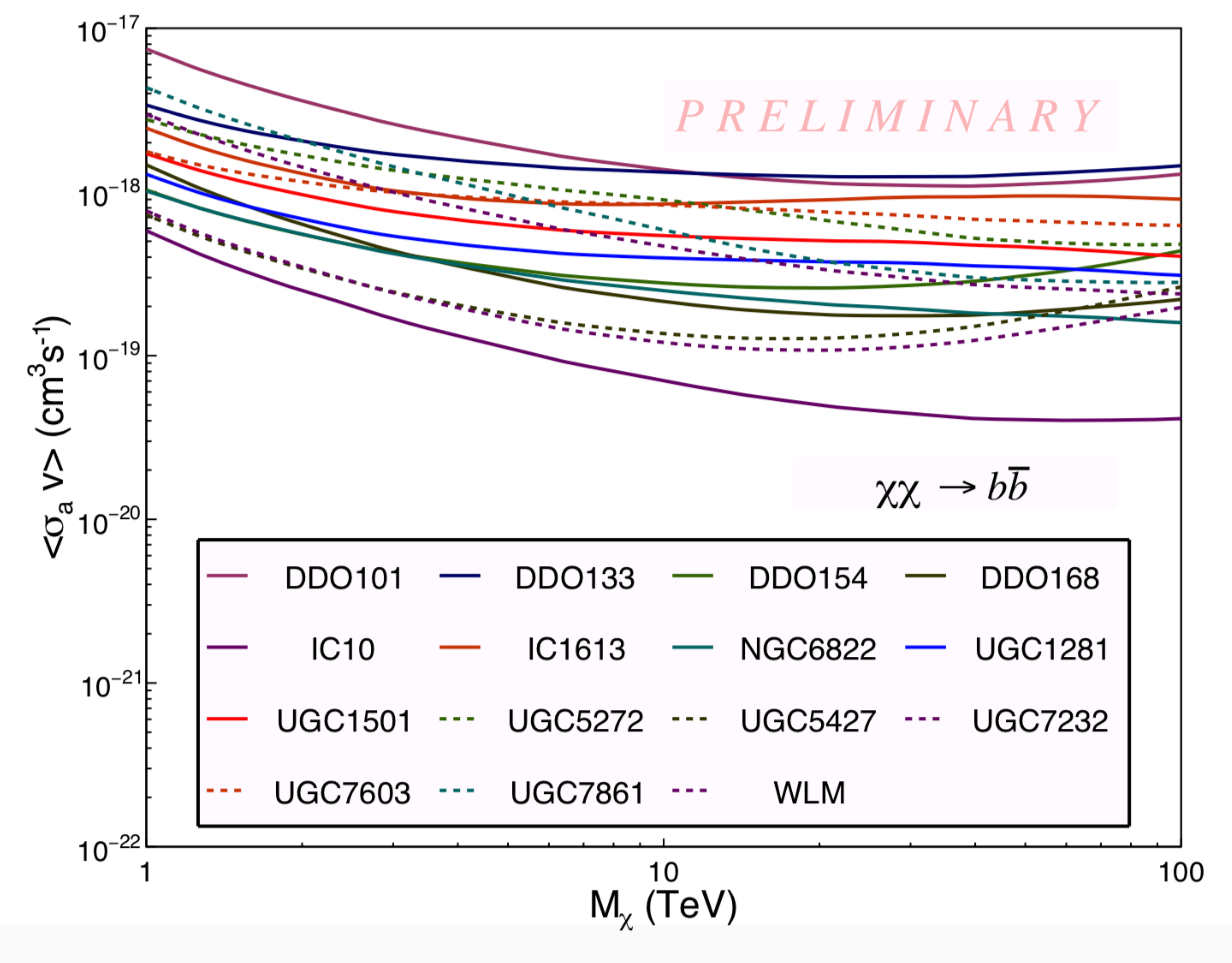
Coefficient

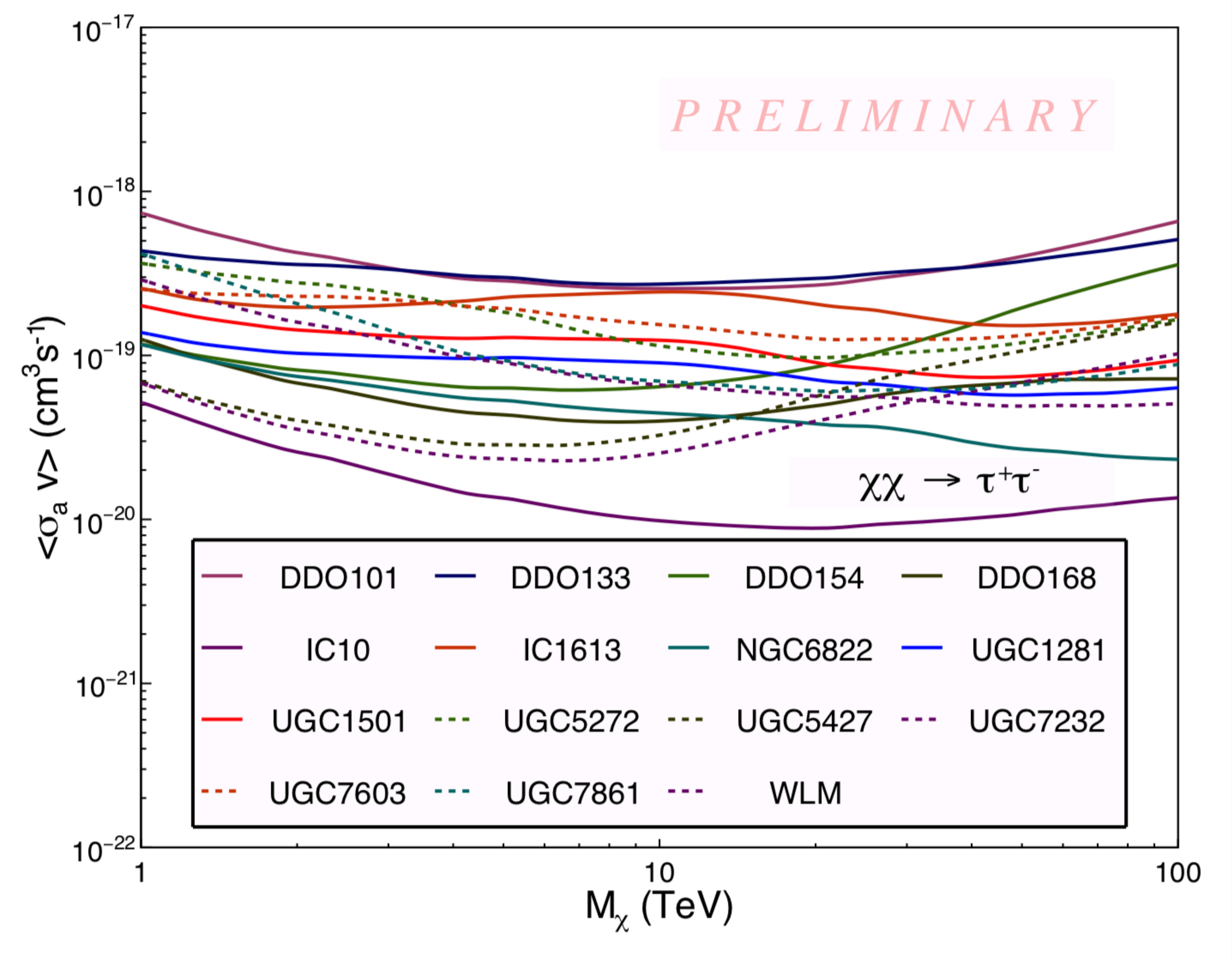
K = 0.04 (fitting parameter)

t_{SF} = 14Gyrs

HAWC – Upper limits

Ref: Gammaldi et al, 2018
ArXiv: 1706.01843





HAWC – Upper limits

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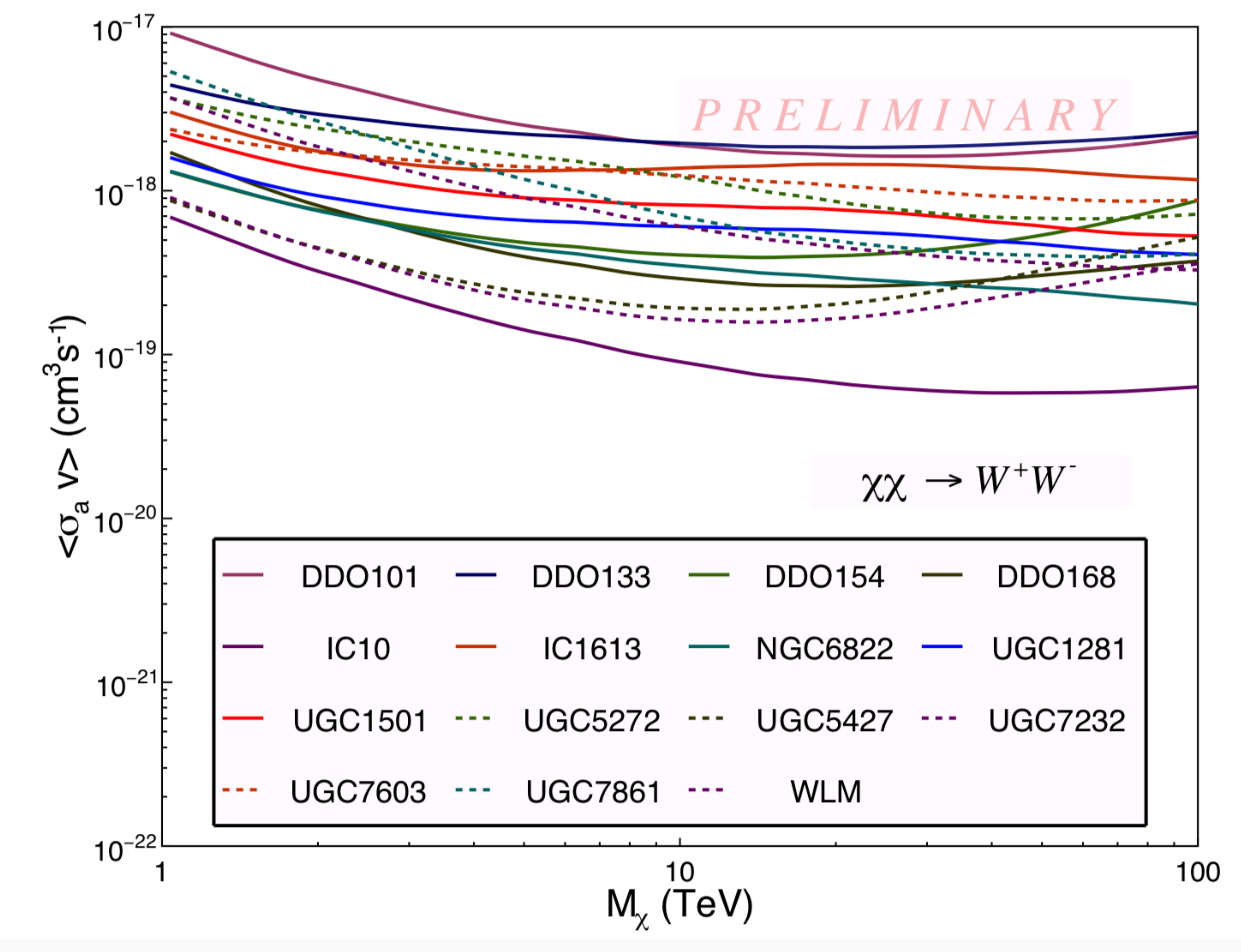

Rvir = 44.2 kpc

J = 4.3553 x 10^{16} GeV^2.cm^{-5}

θvir = 2.5°

HAWC – Uncertainties

Ref: Gammaldi et al, 2018

“Here the error bars represent the uncertainties of the DM density profile. Then, the 15% error on the DM density distribution parameters ρ0 and r0 introduces an uncertainty of 20% – 60% on the density distribution itself, that is 75% of the astrophysical J-factor. We neglect the un- certainties on both the extreme limits of integration along the l.o.s. and the solid angle since these contributions are expected to be negligible.”

“The uncertainties on the virial J-factors in Fig. 4 are calculated as for the point-like analysis. Instead, the error on θvir is obtained by taking into account that the value of the virial radius Rvir in galaxies is independent of the distance to them.”