Dark Matter searches in WLM dwarf irregular galaxy with H.E.S.S.

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- on behalf of the **H.E.S.S. collaboration** -

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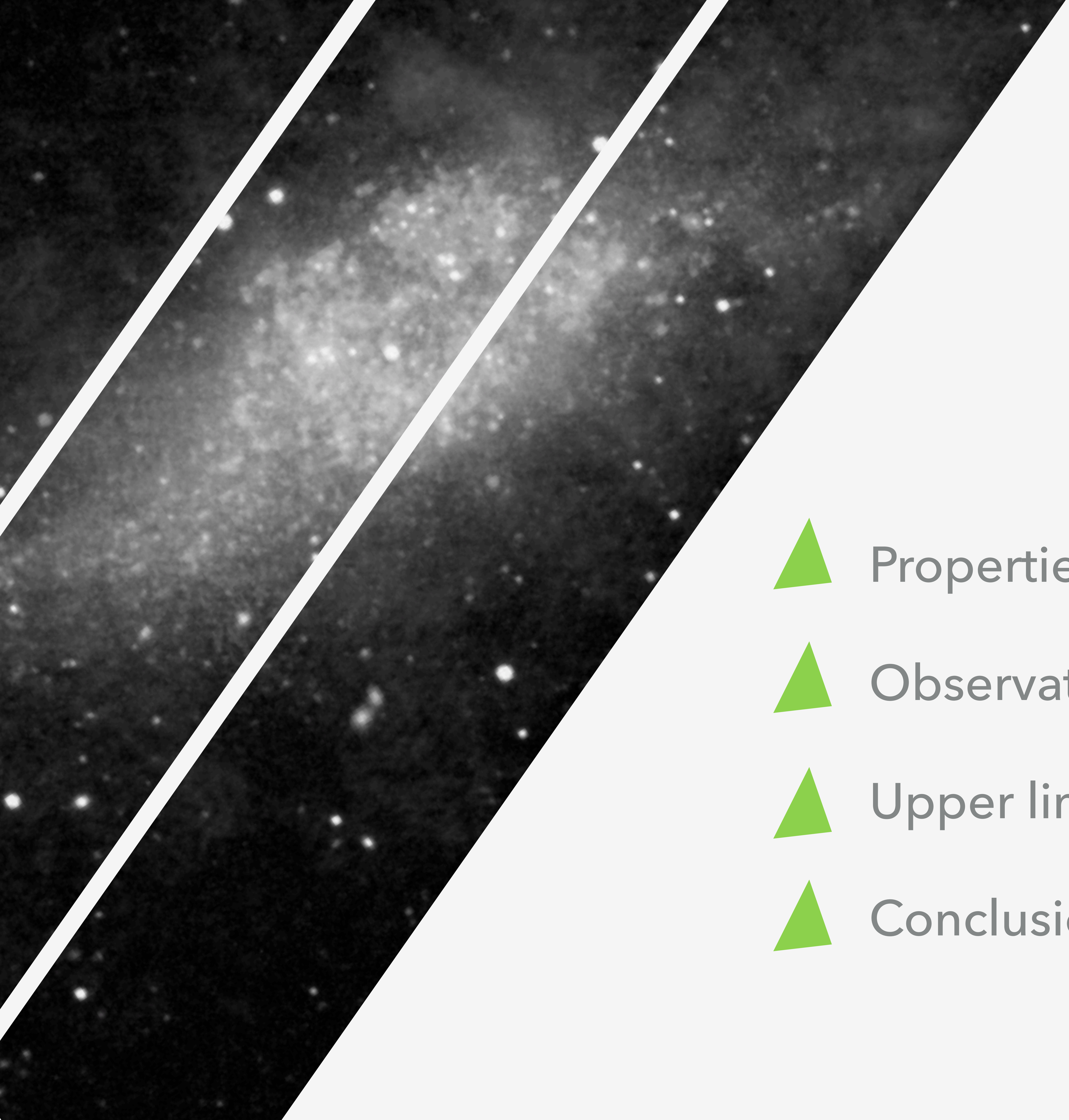


OUTLINE

- Properties & theoretical aspects of WLM
- Observations & data analysis
- Upper limits
- Conclusion and perspectives

PART 1

Properties and theoretical aspects

γ-ray flux

Indirect Detection Framework

$$\frac{d\Phi_\gamma}{dE_\gamma} = \boxed{\frac{1}{2}\frac{\langle\sigma v\rangle}{4\pi m_\chi^2}} \cdot \boxed{\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}} \cdot \boxed{\int_{\Delta\Omega}\int_{\mathrm{los}} \rho_{\mathrm{DM}}^2 \, ds \, d\Omega}$$

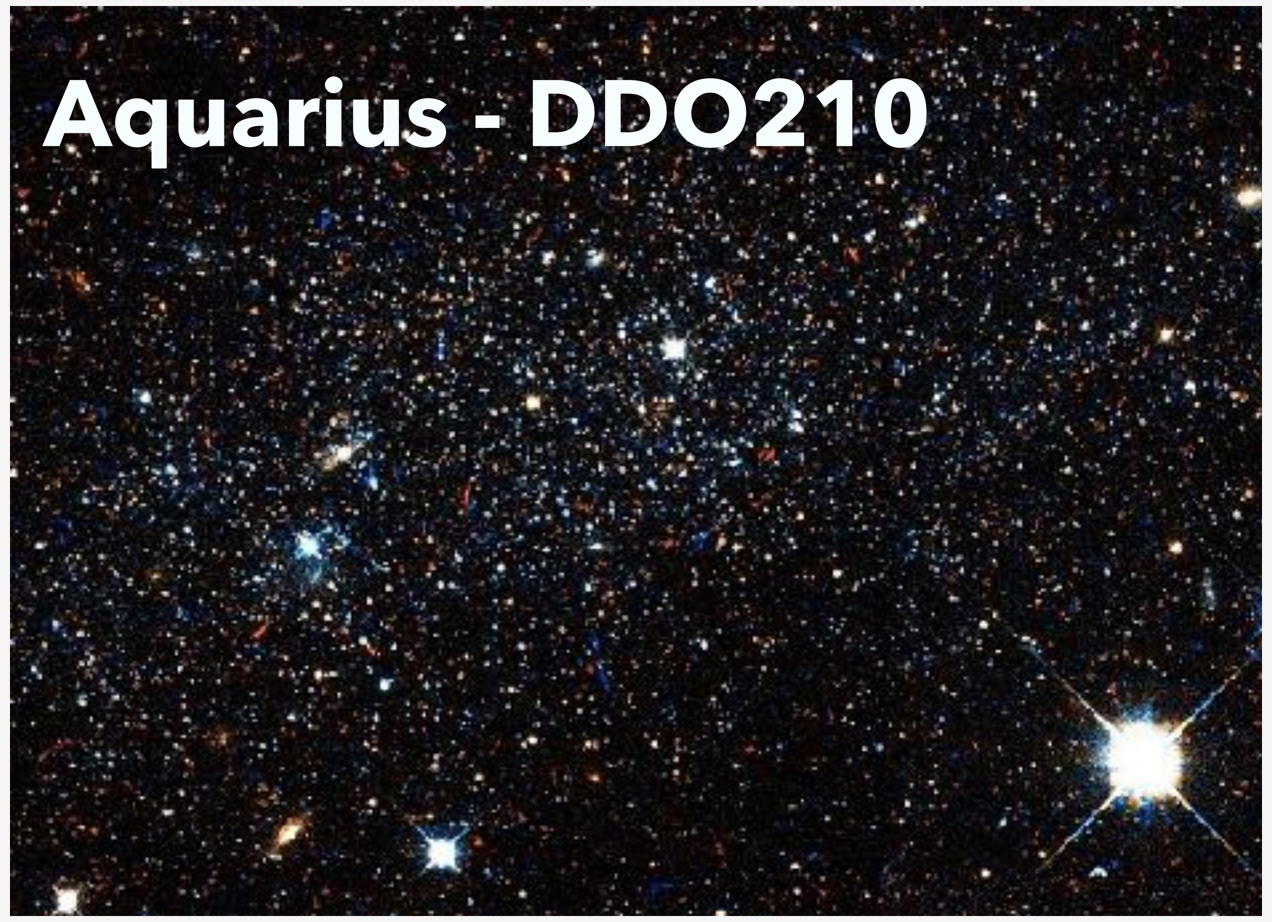
Normalization Factor

Particle Physics Φ_{PP} Factor

Astrophysical J Factor

where

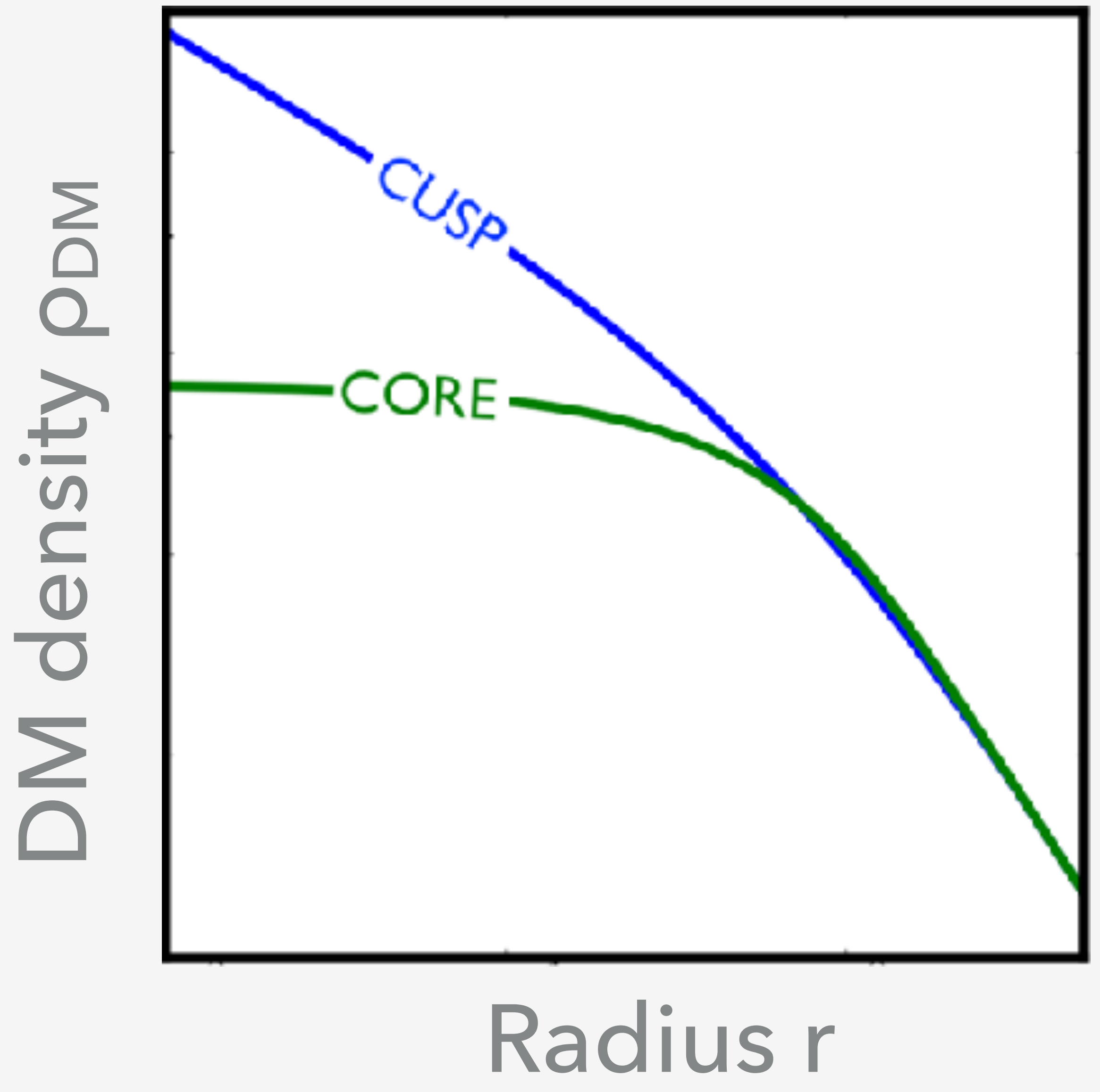
$\langle\sigma v\rangle$ = annihilation cross-section
m_χ = DM particle mass
B_f = branching ratio
dN/dE = differential spectrum
ρ_{DM} = DM density



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: $0.3° < \theta_{\mathrm{halo}} < 6°$
- Tend to follow a cored profile
- Star-forming regions below 0.1° negligible signal for HESS



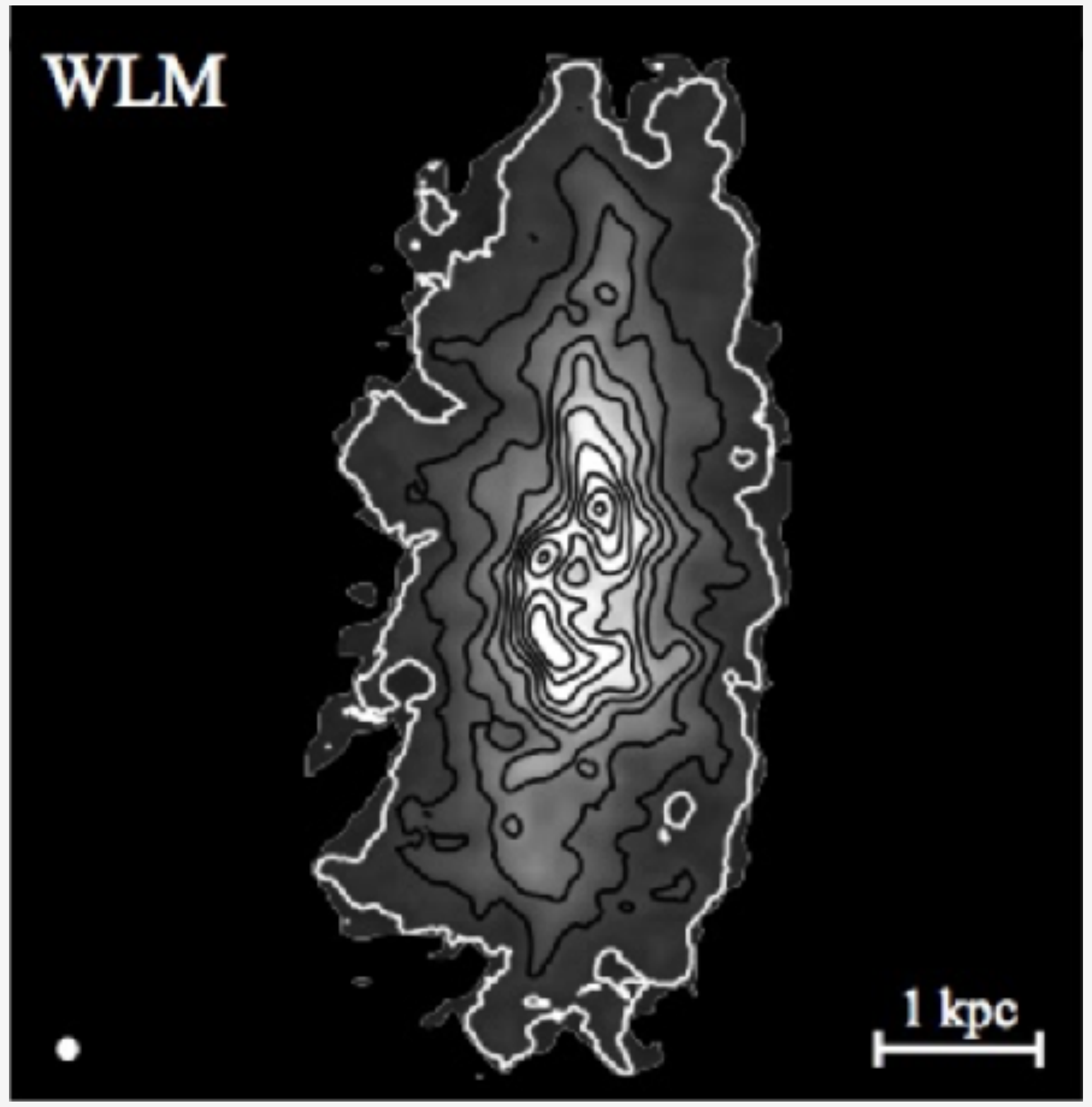
WLM dwarf galaxy

Properties of WLM (Wolf-Lundmark-Melotte)

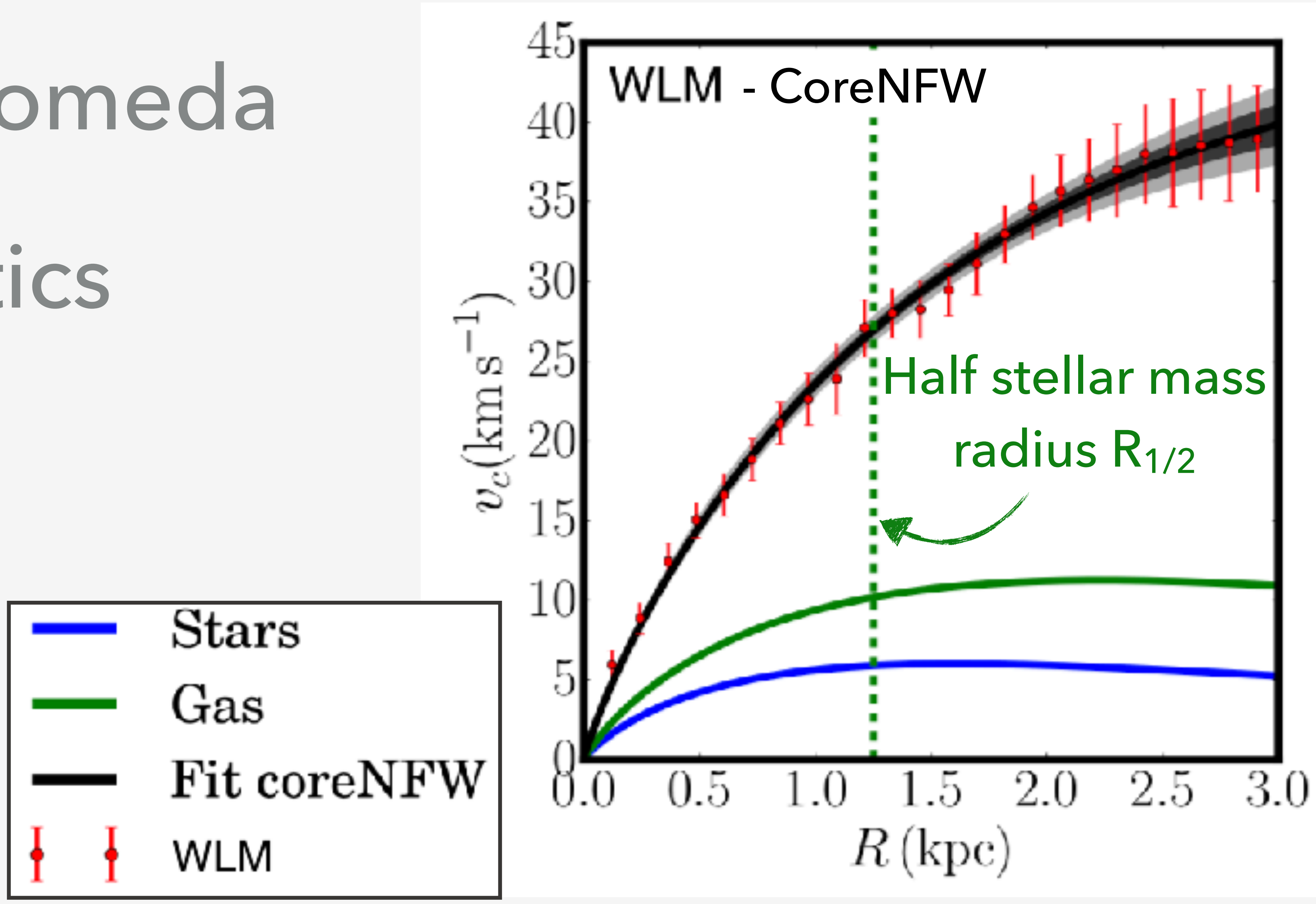
- First irregular dwarf observed by HESS and an IACT experiment
- Isolated source
- Located at ~ 1 Mpc from the Milky Way and Andromeda
- Excellent HI data, photometry and stellar kinematics
- Smooth rotation curve
- Use of a new profile: CoreNFW

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

Smooth HI distribution



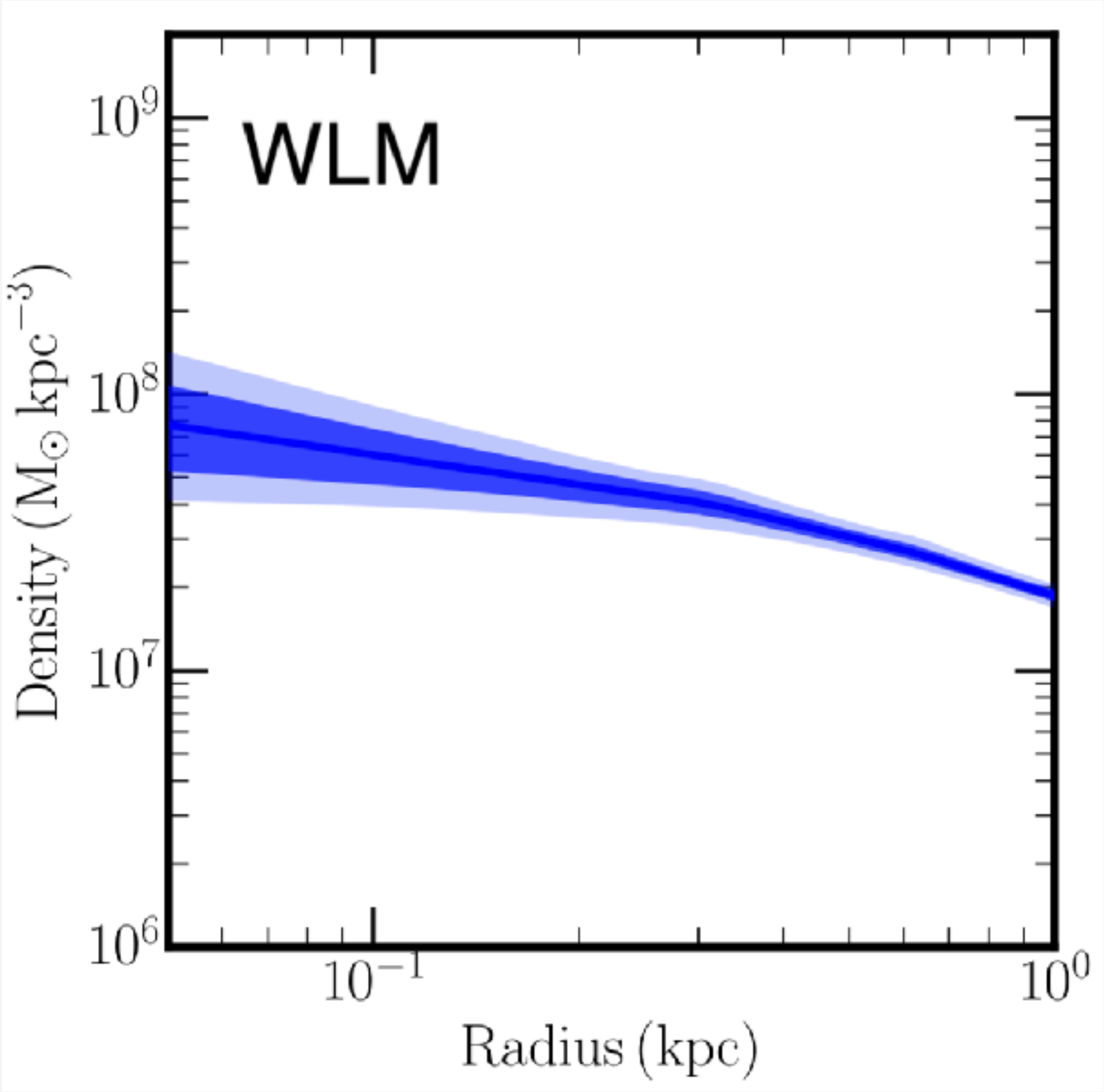
Smooth rotation curve



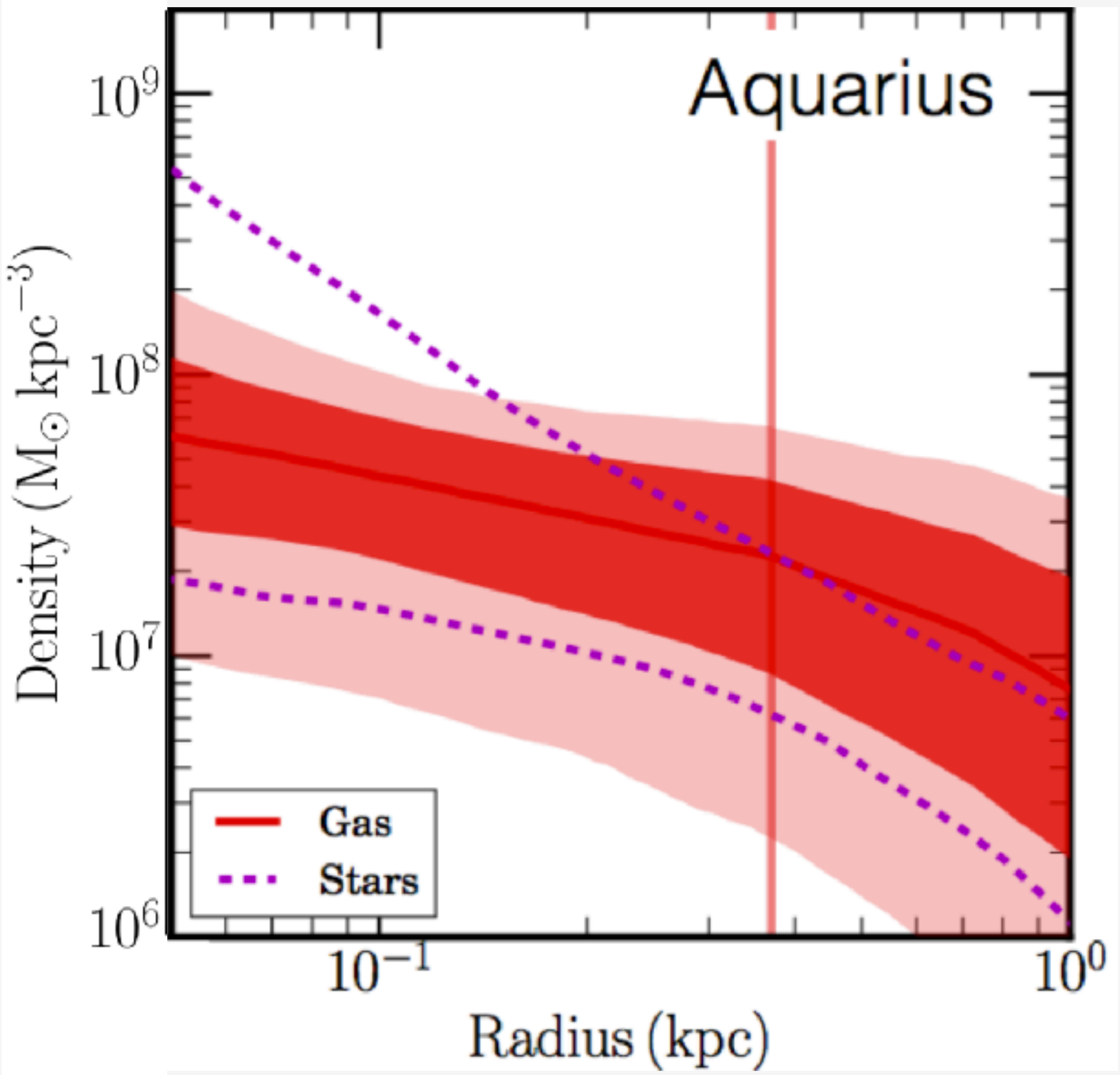
A new DM Profile: CoreNFW

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

A new DM Profile: CoreNFW

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

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

DM component

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

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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

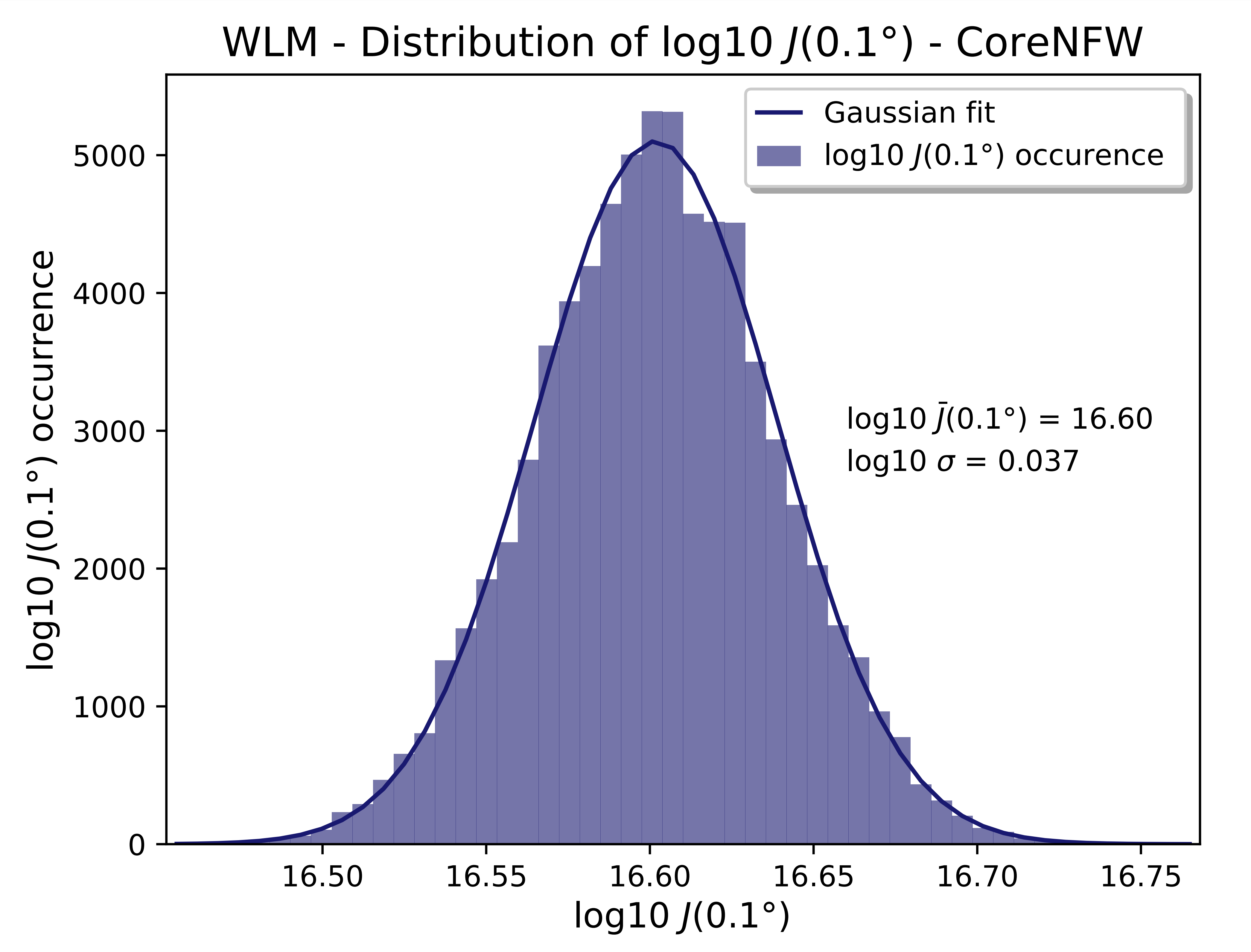
Coefficient

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**

⚠ Uncertainties based on general assumptions for all irregular galaxies

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

PART 2

Observations and data analysis

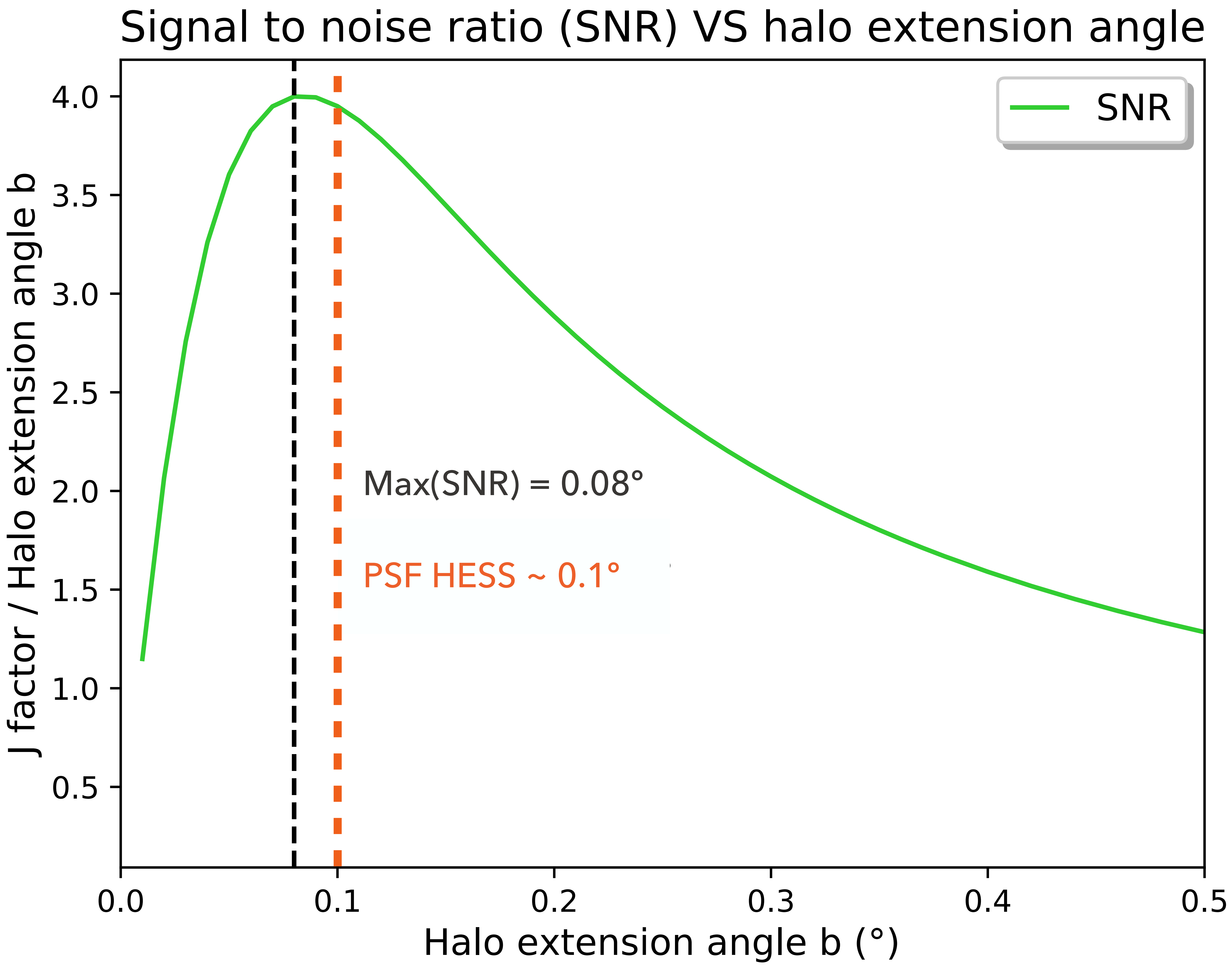
H.E.S.S.

The H.E.S.S. experiment

Array of 5 Cherenkov telescopes

- Located in **Namibia**
- Taking data since **2004**
- Detection of γ rays **~30 GeV to ~100 TeV**

Signal to Noise Ratio (SNR)



WLM as an **extended**

or

a **point-like** source?

Max(SNR) < 0.1°

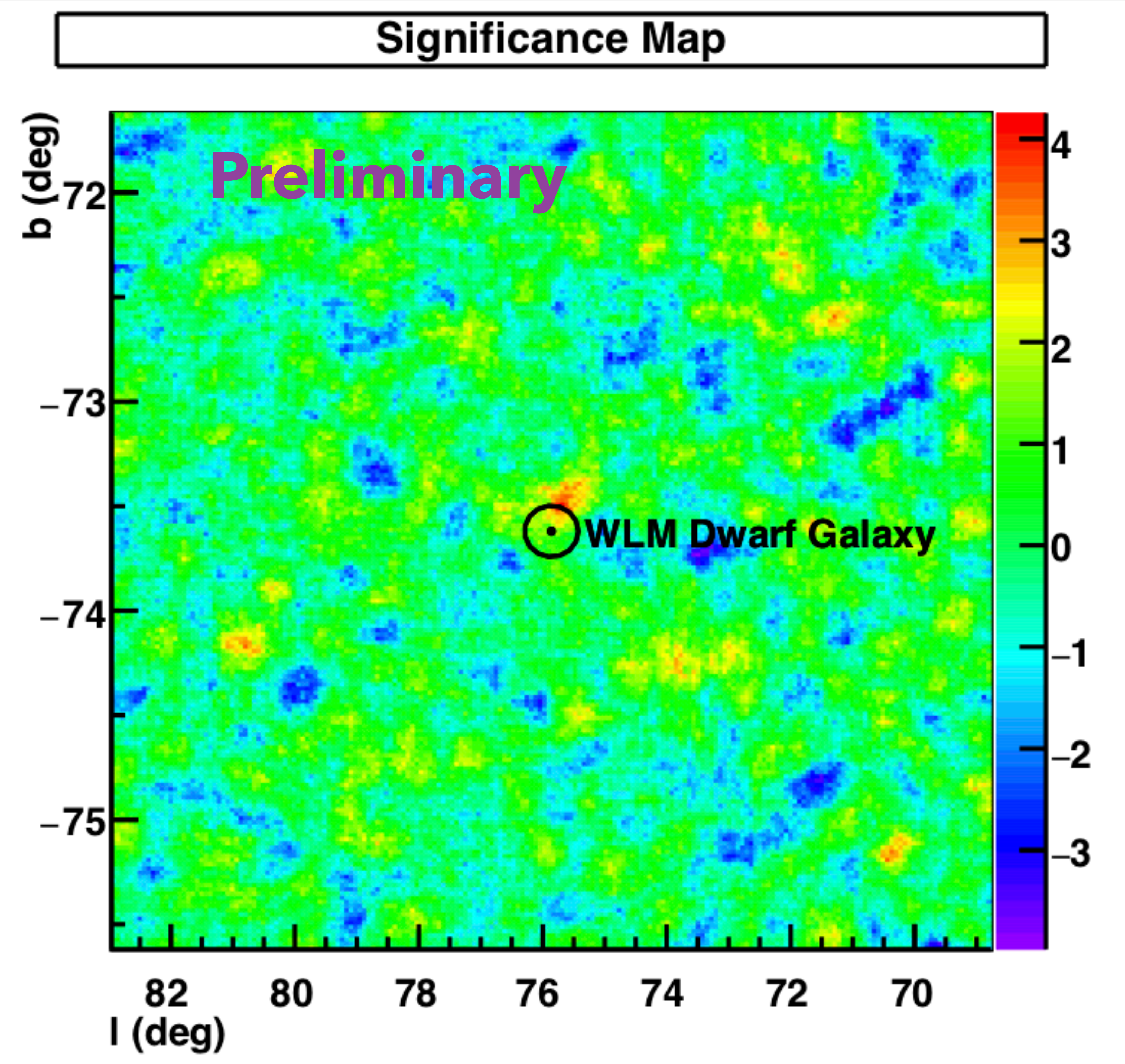
→ WLM treated as a **point-like** source

Contains **50%** of total DM annihilations

Observations & Data Analysis

- **WLM** - Gal. coord. l = 75.86°, b = -73.62°
- Observations from **Oct to Dec, 2018**
- **~ 18** hours
- **Mono Analysis** - Central telescope only (CT5)

Observations & Data Analysis



No significant excess

in the field of view

- Events in the **signal** region: $\mathbf{N_{ON} = 1677}$
- Events in the **background** region: $\mathbf{N_{OFF} = 26726}$
- **Proportionality** between N_{ON} and N_{OFF}: $\boldsymbol{\alpha = 16.24}$
- Rescaled background: $\mathbf{N_{OFF,\,scaled} = 1645.7}$
- γ-ray excess = **31.2 γ**
- **Significance of the excess: σ = 0.7**

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:

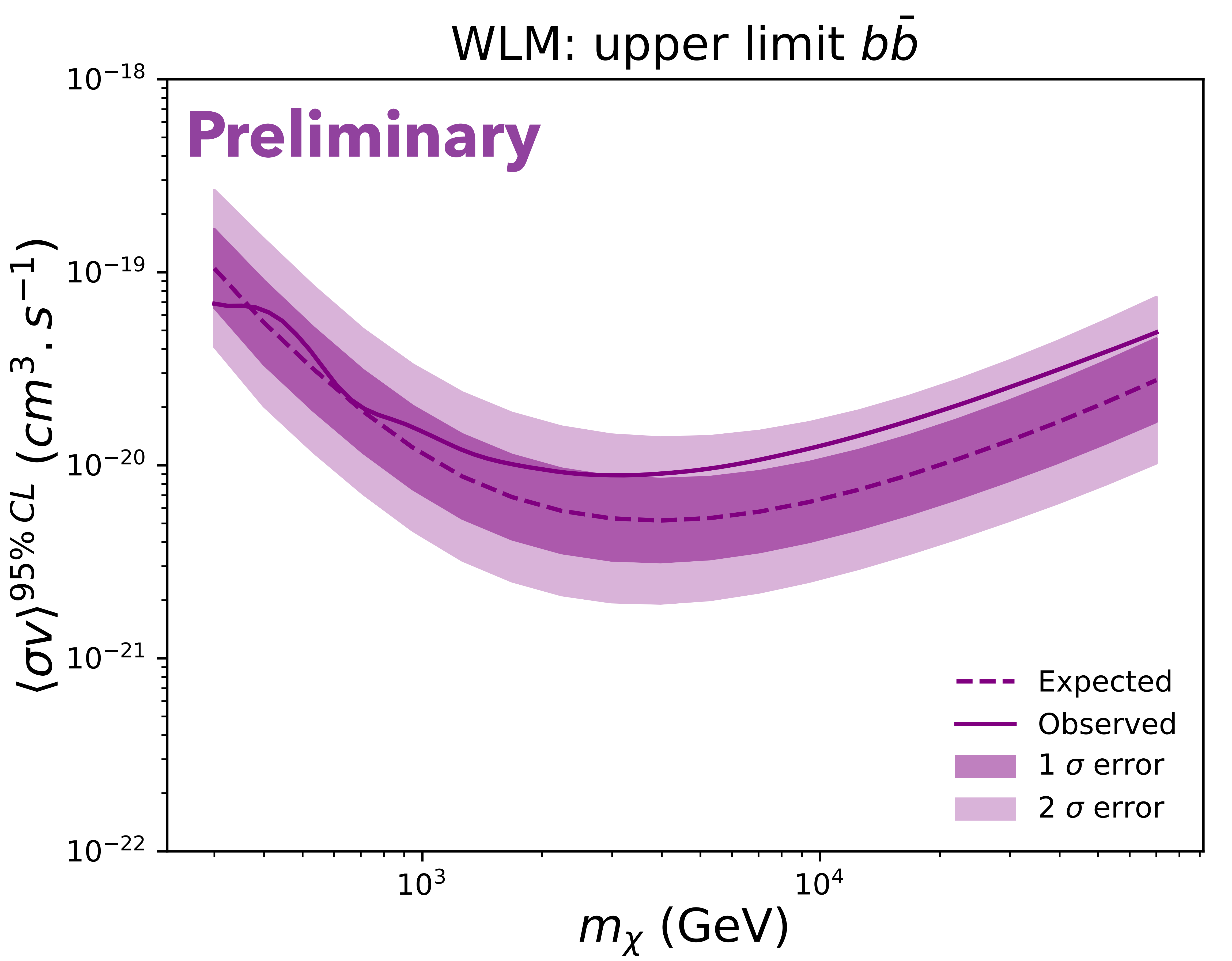
$$\Lambda = -2\ln\frac{\mathscr{L}_{H_0}}{\mathscr{L}_{H_1}} = -2\ln\frac{\mathscr{L}(N_{S_0}\,|\,\hat{N}_B, \hat{J})}{\mathscr{L}(\check{N}_S, \check{N}_B, \check{J})}$$

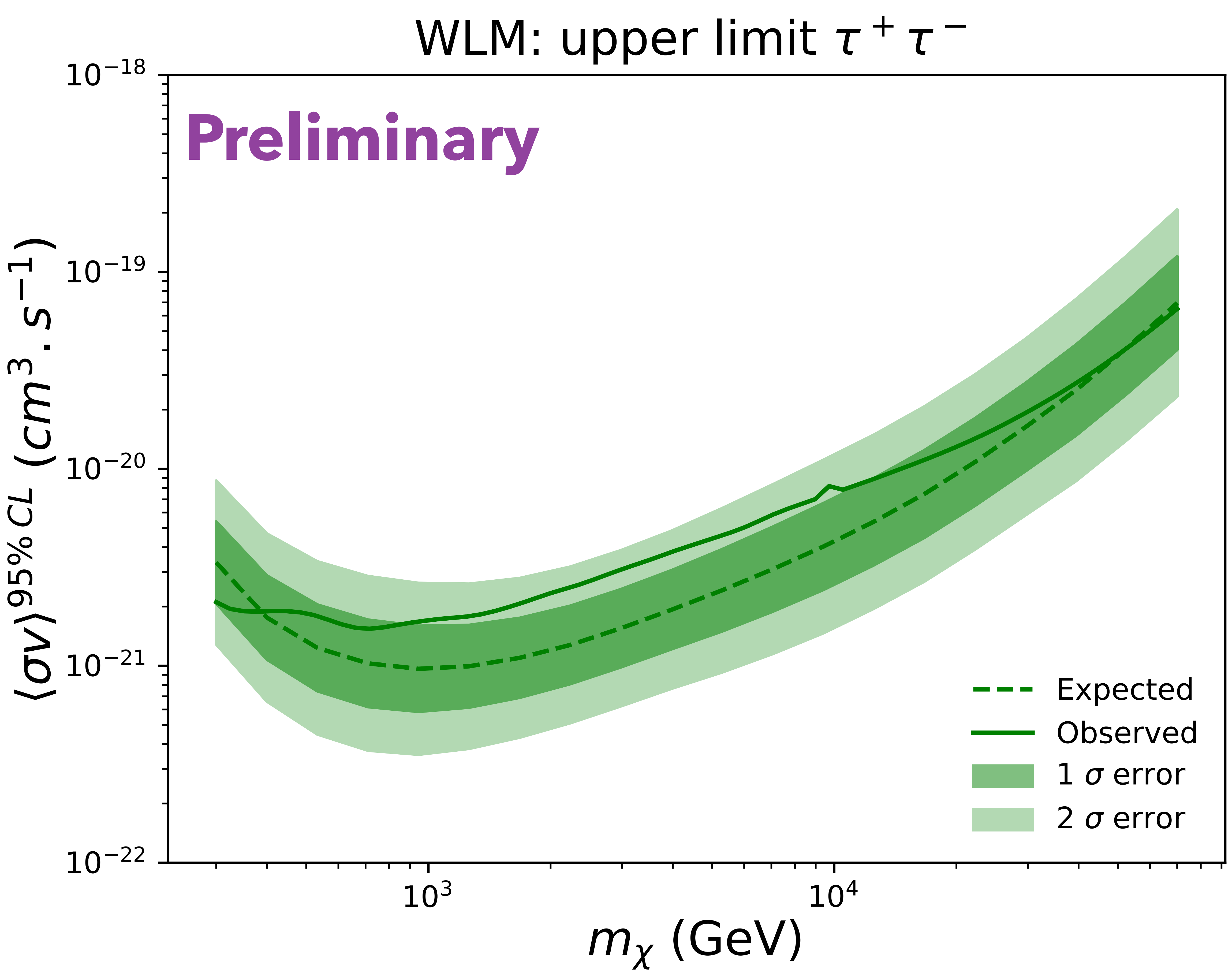
Ref: Cowan et al, 2010
Eur.Phys.J.C71:1554,2011

Upper Limits

Expected and observed limits with J uncertainties

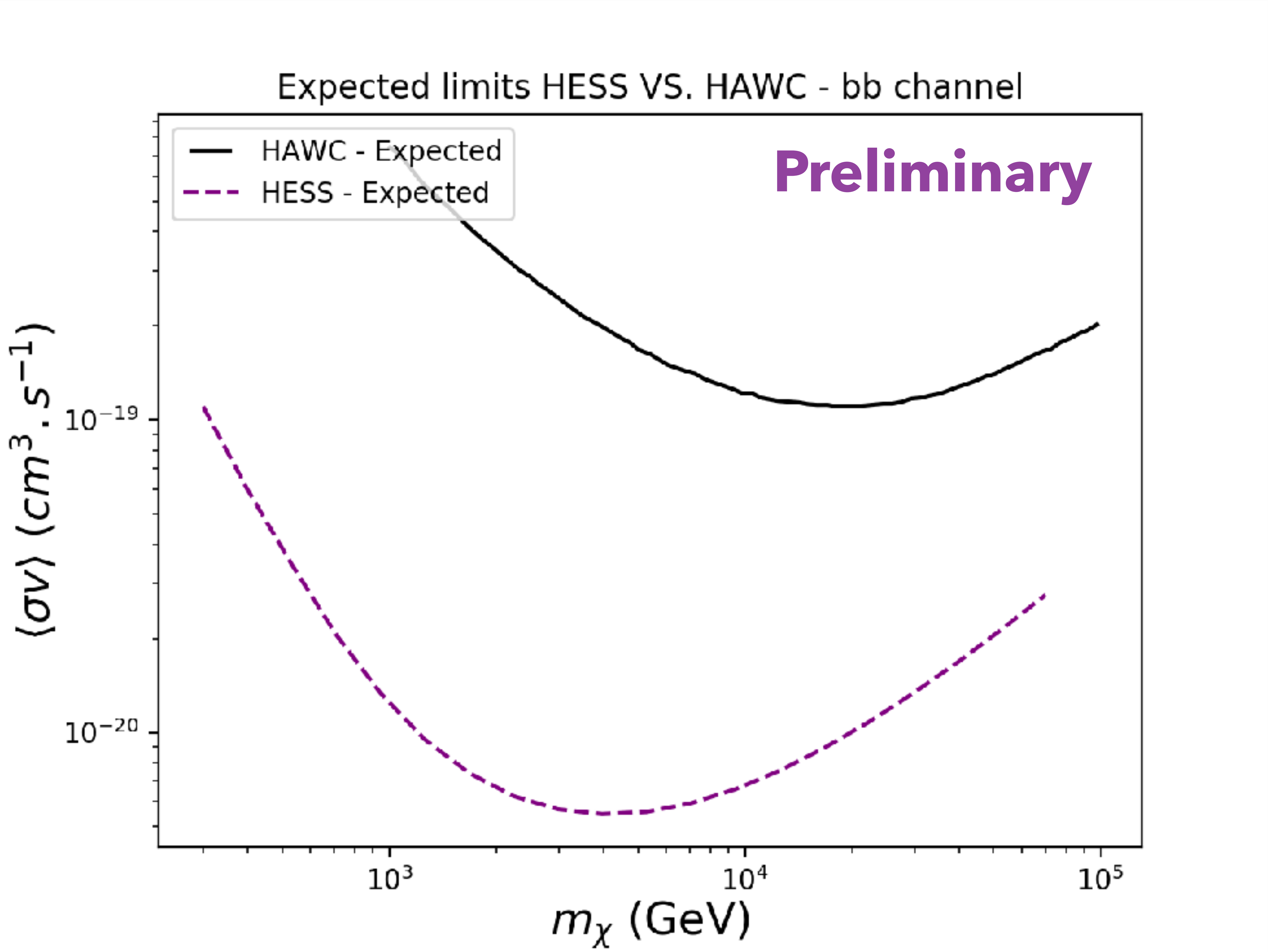
Upper limits for bb and WW channels at 95% C.L.





Comparison to HAWC results

Upper limits at 95% C.L.



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 & Perspectives

Conclusion

- **No excess** has been observed in the data
- **Upper limits at 95% C.L.** for 2 annihilation channels
- WLM as a **point-like** source
- **More competitive** than the upper limits set by HAWC
- **Proceeding** on arXiV (arXiv:1908.10178)

Future plan

- Analysis with the **whole array of telescopes**
- Computation of upper limits with 6 additional channels W^+W^-, Z^+Z^-, tt, e^+e^--, $\mu^+\mu^-$, and $\gamma\gamma$

Thank you

H.E.S.S.

LAPTh

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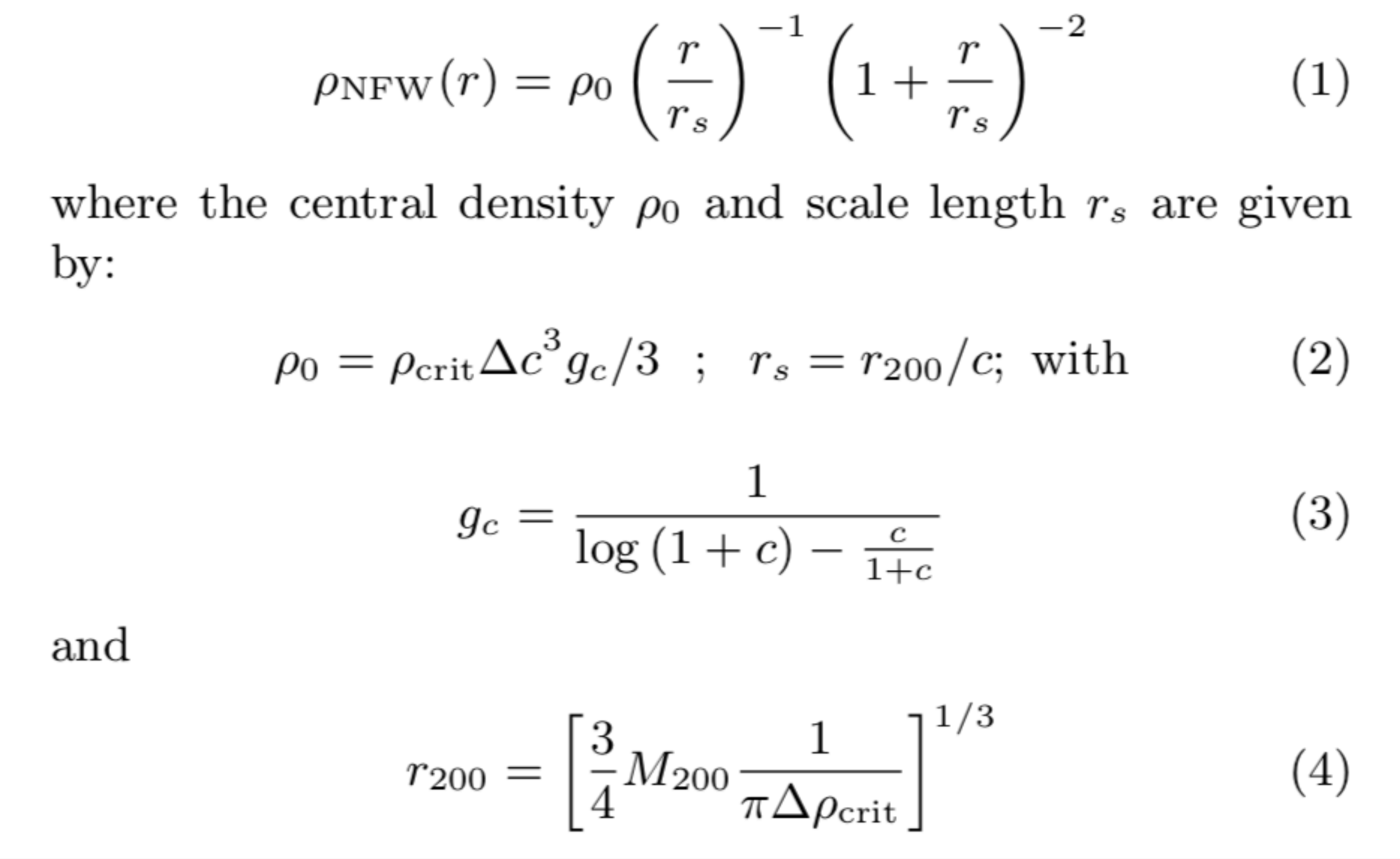
Backup

A new DM 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

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

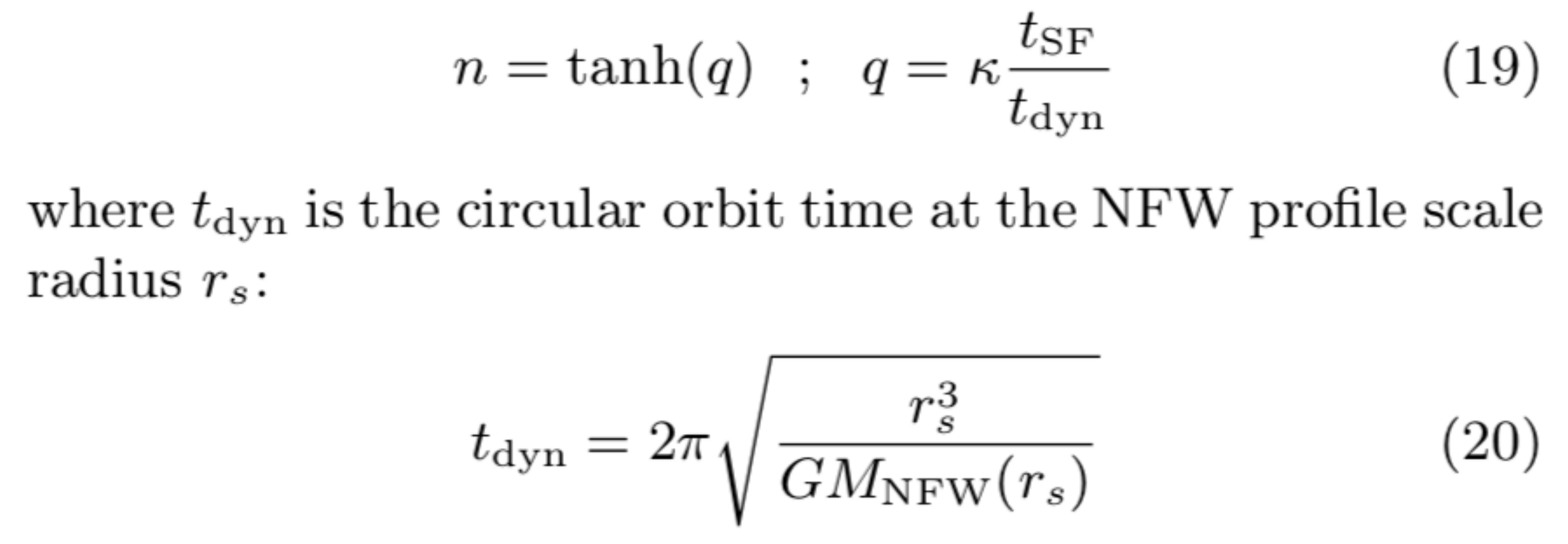
A new DM Profile

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)

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



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

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

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

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

Half stellar mass

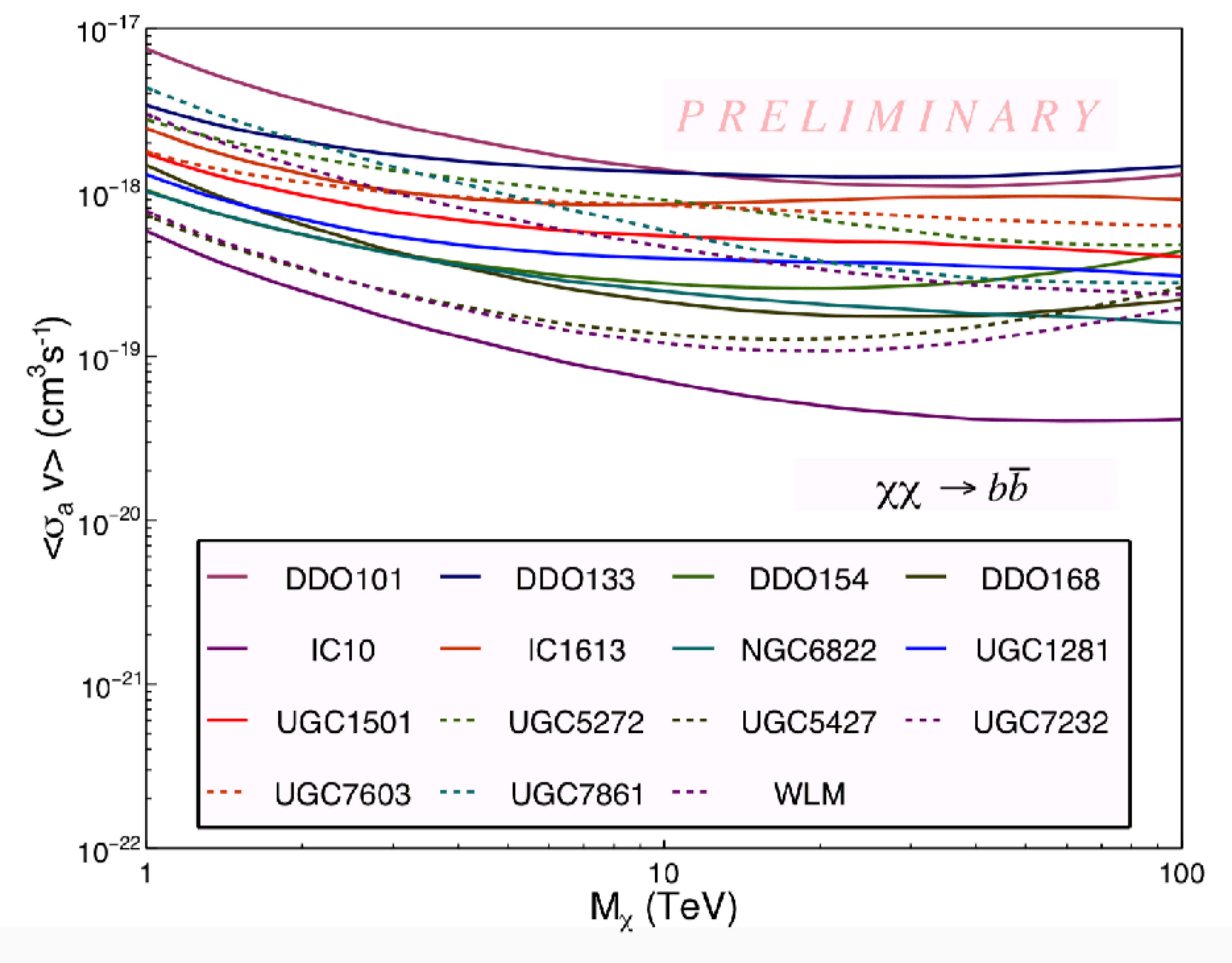
Coefficient

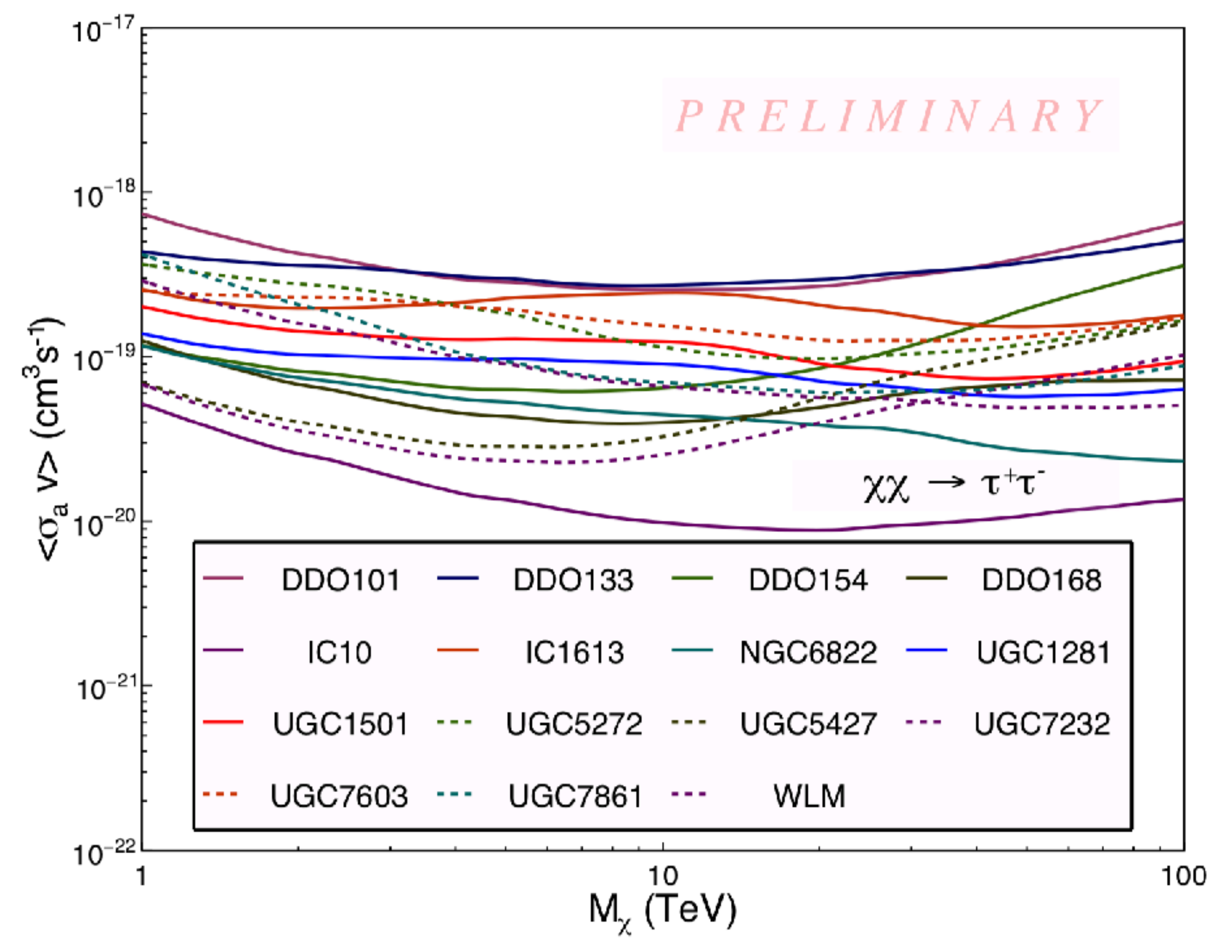
K = 0.04 (fitting parameter)

t_{SF} = 14Gyrs

HAWC – Upper limits

Ref: Gammaldi et al, 2018
ArXiv: 1706.01843





HAWC – Upper limits

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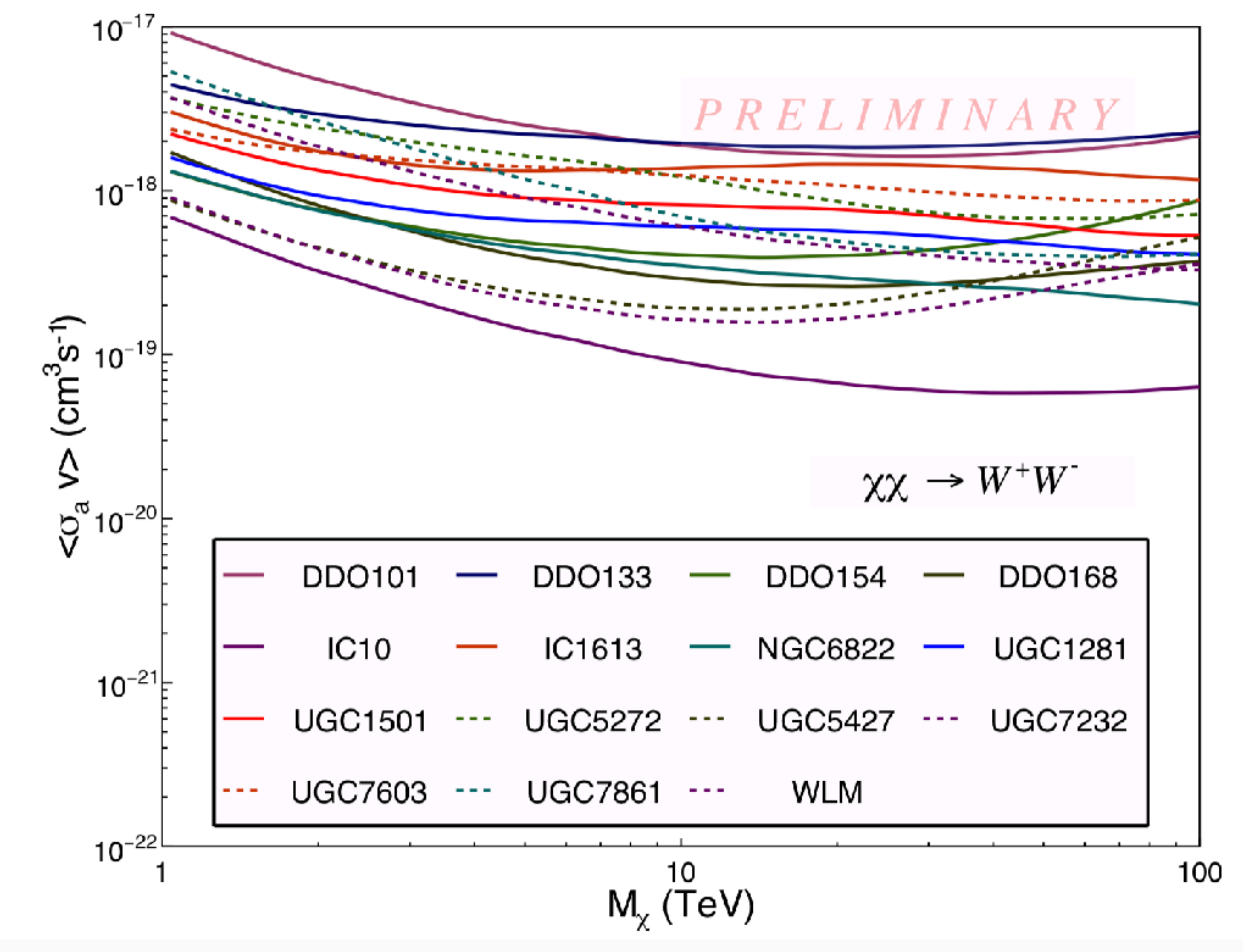

Rvir = 44.2 kpc

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.”