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The structure of the invisible – does dark matter shine?

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The astrophysical evidence for dark matter



Planck Collaboration 2018

	Parameter	Combined	l
$\overline{\Omega_{ m b} h^2}$		0.02233 ± 0.00	0015
$\Omega_{ m c}h^2$		0.1198 ± 0.00	012 <
$100\theta_{\rm I}$	мс	1.04089 ± 0.00	0031
au		0.0540 ± 0.00	074
ln(10	$A^{10}A_{\rm s}$)	3.043 ± 0.02	14
$n_{\rm s}$		0.9652 ± 0.00	042
$\Omega_{ m m} h^2$		0.1428 ± 0.00)11
H_0 []	$\text{km s}^{-1}\text{Mpc}^{-1}$]	67.37 ± 0.54	4
Ω_{m} .		0.3147 ± 0.00	074
Age [[Gyr]	13.801 ± 0.02	24
σ_8		0.8101 ± 0.00	061
$S_8 \equiv$	$\sigma_8(\Omega_{\rm m}/0.3)^{0.5}$	0.830 ± 0.02	13
$z_{\rm re}$		7.64 ± 0.74	4
$100\theta_*$		1.04108 ± 0.00	0031
r _{drag} [[Mpc]	147.18 ± 0.29	9

- Results from a single instrument (Planck/HFI)
- <u>No</u> local/low-redshift data are used
- Linear perturbation of a homogeneous medium
- No exotic/HE physics needed to set pattern
- Outside modified gravity regime
- Modelling cosmic structure formation requires extrapolation to smaller scales and later times

Average mass profiles around bright galaxies



Where is the dark matter predicted to be today?



rms (extrapolated) linear overdensity at z=0 equivalent to smoothing scale

In the Λ CDM model, Press-Schechter theory implies

- $\sim 15\%$ of DM is in clusters
- ~50% is in halos more massive than that of the Milky Way
- ~75% is in halos which contain at least some stars
- Almost 95% is in halos above the Earth mass limit
- The rest is still diffuse today, filling the other 99% of space!

Could the dark matter produce detectable radiation?

3.8



Dark matter decay can produce continuum or line emission.

An X-ray line was claimed to be detected at 3.5 keV in galaxy clusters. \longrightarrow Decay of a sterile neutrino of mass 7 keV? Strongly excluded by nondetection from the MW halo. $L_{halo} \propto M_{halo}$

Dark matter annihilation, for example of SUSY WIMPS, could produce continuum or line radiation in the γ -ray range.

Possibly detection as an excess at 1-10 GeV towards the Galactic bulge.

 $L_{halo} \propto \rho_{halo} M_{halo}$ Luminosity biased to high-density (i.e. low-mass?) halos/subhalos

Very small (sub)halos could be seen by annihilation



- MW's halo annihilation flux may be dominated by that from unresolved small subhalos but this is nearly uniform over the sky
- Flux from the Galactic centre dominates that from resolved subhalos by a large factor, but relative detectability depends critically on noise sources
- The smallest halos may dominate the cosmic annihilation luminosity density

The N=10⁹ Aquarius model for the MW Halo (DM only)





Density profile shapes

Over 19 orders of magnitude in halo mass and 4 orders of magnitude in density, the mean density profiles of halos are fit by NFW to within 20% and by Einasto (with $\alpha = 0.16$) to within 7%

$$L_{ann} = A_{p.p} \int \rho^2 dV$$

= $A_{p.p.} \cdot 1.87 V_{max}^4 / G^2 R_{max}$

across the full mass range

Wang, Bose et al 2020



Concentrationmass relation

Concentrations at small mass are lower than all previous extrapolations by up to factors of tens

A turndown at 10³ Earth masses is due to the free-streaming limit.

The scatter depends only weakly on halo mass.

Sets the $V_{max} - R_{max}$ and so the L_{ann} - M relation for all halos

Wang, Bose et al 2020



Annihilation luminosity per unit cosmological volume as a function of halo mass

The contribution of halos to the mean z = 0 luminosity density of the Universe is almost independent of their mass over the mass range $10^{-4} M_{\odot} < M_{halo} < 10^{12} M_{\odot}$

It is lower than previously estimated by factors between 3 and 1000

This still neglects the substructure contribution to halo luminosity

Wang, Bose et al 2020



High-resolution Auriga simulations

Grand & White 2021

- Six simulations of "Milky Way" formation in ΛCDM $m_{_{DM}} \sim 5 \times 10^4 M_{_{\odot}}, m_{_{bar}} \sim 6 \times 10^3 M_{_{\odot}}$
- Each is simulated twice "full physics" and dark matter only
- Each also includes the nearby "field" environment
- For large objects, $L_{ann} = \int \rho^2 dV$ is estimated by Voronoi tesselation
- For small objects, $L_{ann} = 1.87 V_{max}^4/G^2 R_{max}$ from Einasto fits to $V_c(r)$

How do baryons affect the DM structure of small halos?



• Individual small field halos have slightly larger R_{max} and slightly smaller V_{max} in the full physics simulation $\longrightarrow L_{ann}$ drops by almost a factor of 2

How do they affect the $V_{max} - R_{max}$ relations of (sub)halos?



• The DMO field halo relation matches Wang et al (2020) down to the resolution limit

- The full physics field halo relation is parallel but higher by a factor of 1.4
- Both relations are shifted down by a factor of about 2 for subhalos
- Resolution affects the subhalo relation below $V_{max} \sim 10$ km/s

How do baryons affect MW annihilation luminosities?



- The luminosity of the main halo goes up by a factor of 3
- Its half-light radius goes down by a factor of 5
- The luminosity in resolved satellites drops by a factor of 6
- Satellites are particularly suppressed in the inner regions
- The contrast between the main component and the brightest subhalos increases by 1.5 dex



"Full physics"

Dark matter only

The cooling and condensation of gas into galaxies makes the main halo emission brighter, more concentrated and rounder.

The subhalos become fainter

Extrapolating to the lowest masses – the $n(V_{max})$ function



• DMO -- full phys. drop is larger for subhalos due to enhanced tidal effects

- Abundances converge down to $V_{max} \sim 8 \text{ km/s}$
- Shape of the dashed extrapolations taken from the Wang et al (2020)
 Vmax Rmax M relations together with n(M) from Angulo et al (2012)

Extrapolating to the lowest masses – the $n(L_{ann})$ function



- Upper number in each pair is Ltot/LMW,bar for the resolved subhalos
- The lower number extrapolates all the way down to Earth mass
- Unresolved (sub)halos increase the luminosities by factors of just 2.5 4.5

Extrapolating to the lowest masses – subhalo fluxes



- Fluxes are as observed from a "Solar" position in units of the main halo flux
- The brightest subhalo has expected f/fMW ~ 0.0002 (f.p) or 0.003 (DMO)
- The <u>total</u> subhalo flux is expected to be < 0.2% of the main halo flux (f.p.)
- About half the subhalo flux is in numerically resolved subhalos

Does the main halo profile look like the *Fermi* excess?



Has dark matter been observed directly?

Conclusions

- Baryonic effects substantially enhance and concentrate the predicted luminosity of the main MilkyWay halo in annihilation radiation
- They <u>reduce</u> the luminosity predicted for small halos, V_{max} < 50 km/s
- The enhanced mass concentration of the MW due to baryons leads to enhanced tidal disruption of satellites, especially in the inner halo
- The expected ratio of the flux of the brightest subhalo to that of the main halo is reduced by about 1.5 dex, to ~ 0.0002.
 no subhalo is likely to be detected before the main halo.
- Previous work has greatly overestimated the contribution from very small subhalos, because it overestimated their concentrations.
- The *Fermi* excess could well be annihilation radiation