Astrophysical Probes of Dark Matter

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Astrophysical Probes of Dark Matter

Probed via Gravity

- **Minimum Halo Mass:**
  - warm DM; strongly-interacting DM; fuzzy DM; etc.

- **Halo Shape:**
  - self-interacting DM; fuzzy DM; etc.

- **Compact Objects:**
  - Primordial black holes; etc.

Probed via Standard Model Coupling

- **Indirect Detection:**
  - WIMPs; sterile neutrinos; extra dimensions; etc.

- **Energy Transport:**
  - Axion-like particles; dark photons; millicharged particles etc.
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**Annika’s Talk**

**Kerstin’s Talk**

etc.
Dark Matter Landscape

10^{-21} eV to 10^{67} eV

- QCD Axion
- Ultralight Dark Matter
- Pre-Inflationary Axion
- Post-Inflationary Axion
- Hidden Sector Dark Matter
- Hidden Thermal Relics / WIMPless DM
- Asymmetric DM
- Freeze-In DM
- Black Holes

Astrophysics

Astrophysics provides the only robust, positive measurement of dark matter.

Direct Detection

Astrophysical Probes

Indirect Detection

Particle Colliders

Require Coupling to Standard Model

Dark Matter
Use the Distribution of Dark Matter to learn about the Composition of Dark Matter.
the actual core density, while the lower panel shows the ratio with probe at the same time a volume which is about box is slightly better than that of already at the resolution level that our parent simulation allows. To do this, we measure the central or core density for all resolved main times, where the density is high enough to cause at least some par- side length and depth of.

Figure 6.

10 than 2 between all three resolutions. We find that these criteria identify a quantitative measure of how well the Lagrangian regions of the substructures overlap between the simulations of different resolu-

We have devised the subhaloes themselves. We use a sample of the particles present in these three simulations as the corresponding objects have very similar positions, velocities and masses.

At this epoch it is relatively easy to match the largest substructures of different resolution. The same phenomenon is seen in hot dark matter simulations and is numerical in origin, occurring along the.

of substructures identified in the WDM simulations form through spherical. We have therefore devised a second measure based on mass below 10

the subhaloes with infall masses greater 10

The mass resolution of our uniform simulations and is numerical in origin, occurring along the of spurious haloes in our WDM simulations are typically very as-

the subhaloes with infall masses greater 10

we plot the correlation between

we have found that the shapes of the Lagrangian regions

white 2007). This artificial fragmentation is apparent in Fig. 3.

Frenk & White 1996b, 1997), Boylan-Kolchin et al. (2011) found

the observed dwarf spheroidals follows an NFW profile (Navarro,

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of CDM simulations, and is also a much smaller fraction of

the majority

models (e.g., Dark and Sterile Neutrino). We have devised a second measure based on

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Baryonic* Physics

Astrophysical processes also impact halo structure

**Dark Matter**
- (Dark Matter Only)

**Dark Matter**
- (Dark Matter + Baryons)

**Stars**
- (Dark Matter + Baryons)

Wetzel et al. (2016)

High-resolution cosmological simulations are now able to robustly include core elements of baryonic physics at Milky Way scales (e.g., FIRE/Latte, EAGLE/APOSTLE, etc.)

*Jargon: Astrophysicists use “baryons” to refer to all standard model particles*
Current and Near-Future Experiments

Wide-Area Imaging
- DES/DECam
- Pan-STARRS
- LSST (future)
- Gaia

Spectroscopic Measurements
- SDSS/BOSS
- 30m Telescopes (future)
- Magellan
- Keck (future)
- DESI (future)
- SDSS/BOSS

High Resolution Imaging
- Hubble
- ALMA
- JVLA
- JWST (future)
The Smallest Dark Matter Halos
than 2 sample of 15 relatively massive subhaloes with mass at infall greater between all three resolutions. We find that these criteria identify a distinction, and select as genuine only those subhaloes with strong matches substructures overlap between the simulations of different resolution. The same phenomenon is seen in hot dark WDM simulations and do not have counterparts in the simulations fragmentation of the sharply delineated filaments characteristic of subhaloes works best when comparing the Lagrangian regions of a subsequent paper but, in essence, we have found that matching

White 2007). This artificial fragmentation is apparent in Fig. 3.}

Figure 3. Images of the CDM (left) and WDM (right) level 2 haloes at z = 0. Intensity indicates the line-of-sight projected square of the density and hue the projected density-weighted velocity dispersion, ranging from blue (low velocity dispersion) to yellow (high velocity dispersion). Each box is 1.5 Mpc on a side. Note the sharp caustics visible at large radii in the WDM image, several of which are also present, although less well defined, in the CDM case.
Warm Dark Matter

Proxy for the Number of Halos

Halo Mass

Smaller Halos

Fewer Halos

Wavenumber (inverse length scale)

Suppression of Structure

Baryon Scattering

Fuzzy Dark Matter

Dark matter models that suppress small-scale structure are probed by the existence of the smallest dark matter halos

Nadler et al. (2019)

Armengaud et al. (2017)
How do we measure small halos?
Lyman-α Forest

Hydrogen Absorption in Dark Matter Halos

Spectrograph

Distant Quasar

QSO J1117+1311

López et al. (2016)

Wavelength (nm)

Lyα

z = 2.51
z = 2.86
z = 3.19
z = 3.44
z = 3.62
Lyman-\(\alpha\) Forest

Posterior Likelihood

\[ m_{\text{WDM}} \text{ [keV]} \]

- \( m_{\text{WDM}} > 5.3 \text{ keV} \)

Iršič et al. (2017)
Milky Way Satellites

Simulation of Dark Matter

The Milky Way

???

80 kpc
Satellite Galaxy Discovery Timeline

Predictions from standard CDM + galaxy formation; *no* missing satellites problem

ACDM Prediction (Tollerud et al., 2008)

ACDM Prediction (Hargis et al., 2014)

SDSS Begins

Photographic Plates

Year

Cumulative Number

1920 1940 1960 1980 2000 2020

CONFIRMED

CANDIDATE
Satellite Galaxy Discovery Timeline

Data consistent with *no* missing satellites problem

- SDSS Begins
- DES Begins
- DES Year 1: Bechtol, ADW et al. 2015
- DES Year 2: ADW, Bechtol et al. 2015
- Satellite Galaxy Discovery Timeline

Cumulative Number

Year

1920 1940 1960 1980 2000 2020

Confirmed
Candidate
Constraints on Warm Dark Matter

Only SDSS Satellite Galaxies

Dark matter must cluster on scales at least as small as the dwarf galaxies

$m_{\text{WDM}} > 2.9$ keV

Jethwa et al. 2018
Constraints on Baryon-Scattering

Nadler et al. (2019)

Only using SDSS Satellites
Pushing to Lower Mass

Standard CDM predicts the existence of small subhalos.

How do we detect completely dark subhalos?

Springel et al. (2008)
Strong Gravitational Lensing

Flux Ratios
Suyu et al.; HST
Lin et al. (2009); HST
Gravitational Imaging
Lovell et al. (2012)
Strong Gravitational Lensing

Current Constraints

Hsueh et al. (2019)

\( m_{\text{wdm}} > 3.8 \text{ keV} \)

Ly-\( \alpha \)

7 lensed quasars

Projections for LSST

Hezaveh et al. (from 1902.01055)

Allowed

Hundreds of systems

Ly-\( \alpha \) ruled out at 2\( \sigma \)
Gravitational Perturbations

Rings of Saturn

Shepard moons can be detected by their gravitational wake on Saturn’s rings

Sagittarius Stream

Dark matter substructure can be detected by gravitational disruption of stellar streams

NASA/JPL-Caltech/Space Science Institute

Amanda Smith, IoA, Cambridge

Artists Rendition

DM Subhalo
Gaps in Stellar Streams

Possible gaps in Palomar 5

Image: Belokurov+

Observed stream

Simulated
Regular stream

Simulated
Perturbed stream

Small gap

Large gap

Erkal et al. (2017); Carlberg et al. (2012)

This measurement needs to be made statistically on the population of streams

$10^6 - 10^8 \, M_\odot$ perturber
Gaps in Stellar Streams

Projections for LSST

Current

Ly-α

$\mu$ (mag/arcsec$^2$)

$M_{\text{vir}}(z=0)$ ($M_\odot$)

$\mu_{\text{WDM}}$ (keV)

$\mu_{\text{WDM}} > 18$ keV

$\mu_{\text{WDM}} > 18$ keV

$\mu_{\text{WDM}} > 18$ keV

https://arxiv.org/abs/1902.01055
The Shapes of Dark Matter Halos
Figure 6. DM density projections of the zoom MW-like halo simulations for four different DM models. The suppression of substructure, relative to the CDM model, is evident for the ETHOS models ETHOS-1 to ETHOS-3, which have a primordial power spectrum suppressed at small scales. The projection has a side length and depth of $500 \text{kpc}$.

We can try to quantify this already at the resolution level that our parent simulation allows. To do this, we measure the central or core density for all resolved main haloes in the uniform box simulations, similar to the analysis presented in Buckley et al. (2014). The mass resolution of our uniform box is slightly better than that of Buckley et al. (2014), and we probe at the same time a volume which is about $3.8$ times larger. We can therefore sample a larger range of halo masses and with better statistics. We define the central (core) density within three times the softening length ($8.7 \text{kpc}$). The upper panel of Fig. 4 shows the actual core density, while the lower panel shows the ratio with respect to the CDM case. We take the median value of the distribution within each mass bin. The plot shows the familiar scale of density with mass at a fixed radius, with core densities that vary from $\sim 10^6 h^2 M_{\text{kpc}}^3$ for halo masses around $\sim 10^{10} h^{-1} M_{\odot}$ to $\sim 10^8 h^2 M_{\text{kpc}}^3$ for halo masses around $\sim 10^{14} h^{-1} M_{\odot}$.

Models ETHOS-1 (red) and ETHOS-2 (blue) have a significantly reduced core density compared to the CDM case for low mass haloes. We note that the effect is strongest in the former than in the latter, which points to the primordial power spectrum suppression as the main culprit since the cross section is lower for model ETHOS-1 than for model ETHOS-2. Low-mass haloes in ETHOS-1 are therefore less dense than in CDM, mainly because they form later (analogous to the WDM case). Interestingly, ETHOS-3 shows a different behaviour. Here the core density is most reduced for haloes around $M_{\odot}$.

Vogelsberger et al. (2016)

Cold Dark Matter

Self-Interacting Dark Matter

e.g., Dark photon

Vogelsberger et al. (2016)
Halo Density Profiles

SIDM surpasses central density... but so do baryons


Fitts et al. (2016)
Too Big To Fail

The central regions of dwarf galaxies are less dense than CDM-only simulations

Dark Matter Only

Dark Matter + Baryons

Adding baryons largely resolve this discrepancy
Diversity of Rotation Curves

Rotation curves of dwarf spiral galaxies show more diversity than expected from CDM.

SIDM thermalizes inner regions of halos, tying the baryonic and dark matter distributions.

Oman et al. (2015)
Joint Sensitivity Projections for LSST

Next-generation experiments will be sensitive to WDM and SIDM properties simultaneously.

Recover SIDM/WDM properties with satellite galaxies discovered by LSST.

Simulation

Cyr-Racine et al. (from 1902.01055)

LSST

30m Telescopes
Summary

- Astrophysics and cosmology probe fundamental particle physics of dark matter via gravity.

- Observations and simulations continue to improve our ability to disentangle dark matter physics from baryonic effects.

- Exciting new experiments are under construction!