Dark Matter in the Cosmos

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@AstroKatie
what we know

dark matter is:
...at least to a first approximation

massive (gravitationally attractive & clustering)
cold (slow-moving)
non- (or weakly-) interacting
(no confirmed non-gravitational interactions)
collisionless (passes through itself and other matter)
invisible (does not emit or absorb light)
what we don’t know

Fundamental nature of dark matter

How dark matter formed in the early universe

Whether dark matter has any non-gravitational interaction with standard model (ordinary) particles -- e.g., annihilation, decay, scattering...
lines of evidence

- Rotation curves/galactic dynamics (missing mass)
- Cluster dynamics (missing mass)
- Strong & weak gravitational lensing (missing mass / halo shapes / substructure)
- Cosmological microlensing (mass distribution)
- CMB acoustic peaks (DM/baryon ratio)
- Matter power spectrum & structure formation (DM/baryon ratio)
- Cluster collisions (missing mass / collisionless matter)
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cosmological microlensing
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- Constrain fraction of mass $\alpha$ in compact sources (stars)
- $\alpha < 10\%$
lines of evidence

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odd-numbered peaks boosted relative to even as baryon fraction increases
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...but what is it?

Usual assumption: Weakly Interacting Massive Particles (WIMPs)

New fundamental particle (possibly part of the supersymmetric model, e.g. neutralino)

Interacts only through gravity and weak force

Possibly its own anti-particle – annihilates when in high densities

Can be searched for with: direct detection, indirect detection, collider experiments
dark matter taster menu

• Annihilating (e.g., SUSY neutralino WIMP)

• Decaying (e.g., axino)

• Warm (WDM) (e.g., sterile neutrino)

• Self-interacting (SIDM) (particle + dark sector force)

• Axion (e.g., QCD axion / string axion)

• MACHO (e.g., primordial black holes)
detecting WIMP dark matter

Direct detection: interactions between DM and standard-model particles

Indirect detection: DM-DM annihilation products

Production at colliders: making DM from high-energy standard-model particle collisions

Image credit: Jonathan Feng
direct detection
direct detection
direct detection
direct detection
direct detection: neutrino wall

![Diagram with data points and lines indicating the direct detection of WIMP-like particles.](image-url)

Billard et al. 2013
direct detection: annual modulation
STAWELL UNDERGROUND PHYSICS LABORATORY (SUPL)

SUPL will be Australia’s first underground integrated laboratory within the Stawell Gold Mine in Victoria, hosting Australia’s first-ever direct detection dark matter experiment.

In the Southern Hemisphere, we have a crucial advantage in uncovering the true nature of dark matter, allowing us to address one of the most important unsolved problems of contemporary science.

SUPL will be a national underground integrated facility, it will host experiments for dark matter direct detection, for testing general relativity, ultra low dose radiation for biophysical characterisation as well as a multi-pass very low background underground laboratory, providing for experiments relevant to Big Bang nucleosynthesis.

SUPL will ensure Australia’s leadership in the worldwide efforts to directly detect and characterise dark matter.

Collaborating Organisations
The University of Melbourne • Northern Grampians Shire Council • Stawell Gold Mine • Australian Nuclear Science and Technology Organisation (ANSTO) • Australian National University • National Institute for NuclearPhysics (Italy) • Princeton University (USA) • The University of Adelaide
indirect detection

Clumps of dark matter in or around our Galaxy could be “hot spots” of annihilation.

Nearby annihilation gives an isotropic background.

The strongest signal is from the Galactic Center (but so are the strongest backgrounds).

Image credit: Fermi Collaboration

Kuhlen, Madau & Silk 2009
cosmic rays

The **AMS instrument** (and several others) saw an excess of positrons in their measurements -- could it be dark matter annihilation?

Maybe -- or could be astrophysical processes
cosmic rays

3 TeV DM with high cross-section proposed as explanation

*Leptophillic* dark matter?
cosmic rays

3 TeV DM with high cross-section proposed as explanation

Leptophillic dark matter?

Image credit: NASA
cosmic rays

But: **pulsars** also make electron-positron pairs

Limited **directional information**

Grasso et al. 2009
cosmic rays

But: **pulsars** also make electron-positron pairs

Limited **directional information**

A couple of nearby pulsars could produce entire signal

Grasso et al. 2009
to the fitting result, the spectral indices are almost the same.

Figure 3: Single pulsar model can explain the positron fraction very well.

III. ANTIPROTON AND POSITRON FITTINGS

The positron fraction rises at higher energies than that of the antiproton. It is remarkable that we can automatically fit the observational data of both the positron fraction and the antiproton fraction by the same set of the parameters [4].

The positron and the antiproton can be consistently explained by the single pulsar model. We take the magnetic field outside the DC as a spherical DC, with the distance to the front of the DC set to be 40 pc. The target proton density is set to be $5 \times 10^5$ cm$^{-3}$ and the maximum energy of the cosmic-ray protons accelerated by SNRs and a dense DC is $100$ TeV (See [4] for the further details).

We have discussed the anomaly of the antiproton fraction recently-reported by the AMS-02 experiment. By fitting the observational data of both the positron fraction and the antiproton fraction, we find that both positrons and anti-protons are produced by the same pulsar. This does not depend on the propagation model since both antiparticles propagate in a similar way below the cooling cut-off energy. From this figure, we find that both positrons and anti-protons are produced by the same pulsar.

Regardless of the model details, the ratio of antiprotons to protons can be produced from the DC without a fine tuning in the model parameters. The observed antiproton excess should entail the positron excess. Only for background cosmic-ray protons accelerated by SNRs and a dense target. The boron to carbon ratio as well as the Li to carbon ratio have no clear excesses [1]. This suggests that the boron to carbon ratio as well as the Li to carbon ratio have no clear excesses [1].

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more excesses

Galactic Center: gamma-ray excess peaking at 1-3 GeV (Daylan et al. 2014)

Galaxy clusters: x-ray excess at 3.55-3.57 keV (Bulbul et al. 2014)
3.5 keV cluster x-ray excess

X-ray excess in galaxy cluster cores at around 3.5 keV

7.1 keV sterile neutrino decay?

In favor: excess in many clusters; backgrounds well studied

Against: scaling of signal strength to mass not as expected; nearby emission lines could contaminate

Bulbul et al. 2014
1-3 GeV Galactic Center excess

Gamma-ray excess in Galactic Center at 1-3 GeV

31-40 GeV WIMP annihilation?

**In favor:** spatial distribution looks plausible; fairly simple WIMP model

**Against:** Galactic Center is messy; complicated analysis that requires verification

Daylan et al. 2014
I-3 GeV Galactic Center excess

young pulsars: how much can they contribute?

O’Leary et al. 2015
dark matter production

If we can’t detect a DM particle, why not make one?

The Large Hadron Collider will collide protons at high energies, possibly producing WIMPs

A missing energy signature would indicate the presence of a new particle

...but nothing seen yet, and no sign of supersymmetry...
dark matter in cosmology: inert scaffolding or active physics?
dark matter particle physics in cosmology

Question I’m trying to answer:
If dark matter is annihilating when the first stars and galaxies are forming, where does all that energy go?
cosmic dawn

dark matter annihilation can cause heating and ionization during the cosmic dark ages

observing the epoch of reionization is a key project for SKA -- great opportunity to see effects of dark matter particle physics
annihilation over cosmic time

power $\propto (\text{density})^2$

“smooth” component

total signal

“structure” component

power

$eV/s/\text{H}^4$

redshift

present  first stars  early times
annihilation over cosmic time

Varying:
- density profile
- mass-concentration relation
- mass function
- lower-mass cut-off

power

redshift

present first stars early times

eV/s/H\,H^4

10^{-12}

10^{-14}

10^{-16}

10^{-18}

10^{-20}

10^{-22}

10^{-24}
annihilation over cosmic time

annihilation within halos

Question:
If dark matter is annihilating within baryonic halos, does this constitute an effective “feedback” process?

Resources:
PYTHIA code: dark matter annihilation events
MEDEA2 code: energy transfer to baryons
Halo models: density profile, mass-concentration
annihilation within halos

Sarah Schon et al. 2014
MNRAS [arxiv:1411.3783]

Ratio: dark matter annihilation energy (over Hubble time) to gas binding energy

molecular cooling possible
Ratio: \text{dark matter annihilation energy} \ (\text{over Hubble time}) \to \text{gas binding energy}
dark matter annihilates
dark matter annihilates

- radiation background
- low-mass cut-off
- heating/ionization of intergalactic gas
- $\text{H}_2$ abundance

- internal heating of dark matter halos
- structure of first stars
- black hole formation

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internal heating of dark matter halos

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unified simulation of galaxy formation & evolution

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black hole
formation

internal heating
of dark matter
halos

dark matter
annihilates

unified simulation
of galaxy formation
& evolution

high-redshift
21cm signal

high-redshift
galaxies
dark matter annihilation

radiation background

low-mass cut-off

heating/ionization of intergalactic gas

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internal heating of dark matter halos

black hole formation

unified simulation of galaxy formation & evolution

high-redshift 21cm signal

high-redshift galaxies

Image credit: Swinburne/ICRAR/Cambridge/ASTRON

SKA
dark matter annihilation

radiation background

internal heating of dark matter halos

low-mass cut-off

structure of first stars

heating/ionization of intergalactic gas

H₂ abundance

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high-redshift 21cm signal

high-redshift galaxies

Image credit: NASA
long-term outlook

Ultimate goal:
Develop a self-consistent picture of dark matter’s particle physics interactions with baryons in the context of the growth of structure in the Universe.

Major outputs:
- New simulations of reionization/galaxy evolution
- Predictions for SKA and precursor instruments
- New perspective on dark matter/baryon interactions
take-home messages

• The **fundamental nature** of dark matter is still a mystery (but we are getting clues)

• To identify dark matter from astrophysics, we need **multi-messenger signals** and a solid understanding of **astrophysical foregrounds**

• The **particle physics of dark matter** must be included and understood for a consistent picture of cosmology