University of Sheffield

Particle Astrophysics

SUSAN CARTWRIGHT
UNIVERSITY OF SHEFFIELD

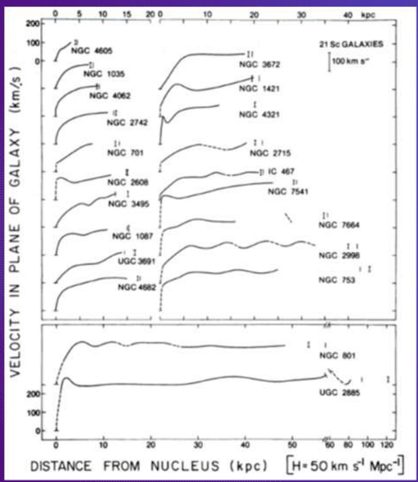
2

Dark matter

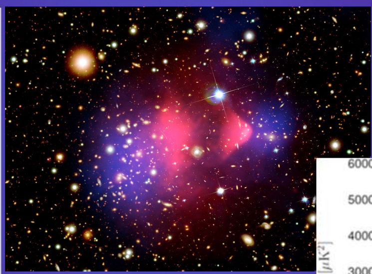
THE ASTROPHYSICAL EVIDENCE
THE CANDIDATES
WIMPS
AXIONS

Astrophysical evidence for dark matter

3

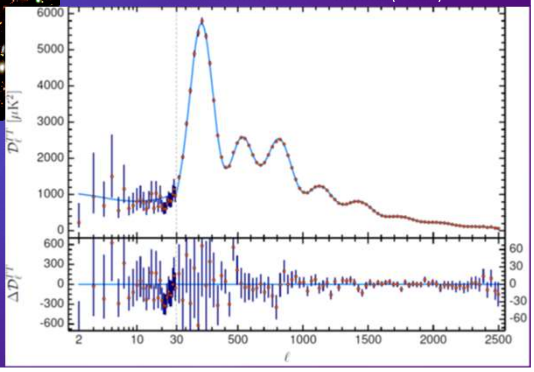


Rubin, Ford & Thonnard, *ApJ* **238** (1980) 471



X-ray: NASA/CXC/CfA/M.Markevitch, Optical and lensing map: NASA/STScI, Magellan/U.Arizona/D.Clowe, Lensing map: ESO WFI

Planck Coll. *A&A* **641** (2020) A6



Dark matter candidates

4

	WIMPs	SuperWIMPs	Light $\tilde{G}$	Hidden DM	Sterile ν	Axions
Motivation	GHP	GHP	GHP/NPFP	GHP/NPFP	ν mass	Strong CP
Natural Ω	Yes	Yes	No	Maybe	No	No
Production	Freeze-out	Decay	Thermal	Various	Various	Various
Mass range	GeV – TeV	GeV – TeV	eV – keV	GeV – TeV	keV	μeV – meV
Temperature	cold	cold/warm	cold/warm	cold/warm	warm	cold
Collisional				✓		
Cosmology		✓✓		✓		
Direct	✓✓			✓		✓✓
Indirect	✓✓	✓		✓	✓✓	
Collider	✓✓	✓✓	✓✓	✓		

GHP: Gauge Hierarchy Problem
NPFP: New Physics Flavour Problem

from Feng, *Ann. Rev. Astron. Astroph.* **48** (2010) 495

WIMPs

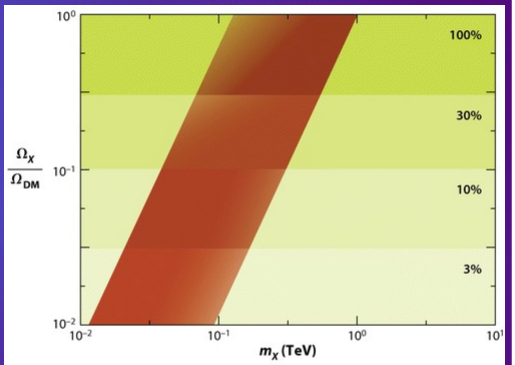
5

Weakly Interacting Massive Particles are a prediction of many extensions to the Standard Model

- they tend to arise from discrete quantum numbers, e.g. *R*-parity, introduced to prevent undesirable features such as rapid proton decay.

A nice feature of WIMPs is that if their annihilation cross section is of the typical weak scale, they naturally freeze out to give the "right" relic density

- this is sometimes called the "WIMP miracle".



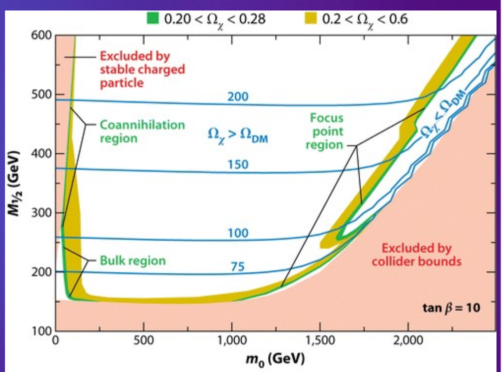
Feng JL. 2010.
Annu. Rev. Astron. Astrophys. 48:495–545

WIMPs in SUSY

6

Supersymmetry solves the GHP by cancelling the quadratic terms in the Higgs self-energy.

- A discrete quantum number, *R*-parity, is introduced to prevent rapid proton decay.
- This makes the lightest supersymmetric particle, usually the lightest neutralino $\tilde{\chi}_1$, absolutely stable.
  - It is a Majorana particle and annihilates with itself.
  - The annihilation cross section is spin suppressed, and Ω tends to be too large, at least in minimal SUSY.



Feng JL. 2010.
Annu. Rev. Astron. Astrophys. 48:495–545

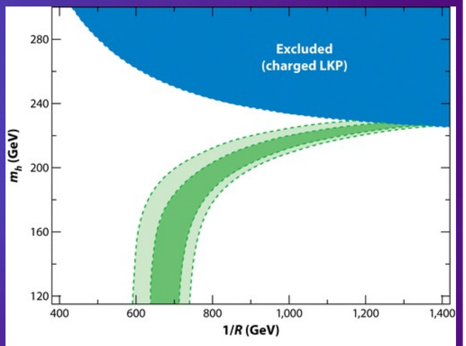
SUSY ⇒ WIMPs, WIMPs ⇏ SUSY

7

Other extensions to the Standard Model also yield WIMP candidates (sometimes naturally, sometimes after a bit of persuasion!), e.g.

- 5- or 6-dimensional Universal Extra Dimension models
- "Little Higgs" models (in which a light Higgs boson arises from spontaneous breaking of a new global symmetry)

Fortunately the experimental signature of such non-SUSY WIMPs is the same as SUSY WIMPs, at least for direct detection experiments.



Feng JL. 2010.
Annu. Rev. Astron. Astrophys. 48:495–545

Detection of WIMPs

8

WIMPs in the Galactic halo are gravitationally bound to the Galaxy and are therefore moving at a few hundred km/s.

- Their only possible interaction is elastic scattering.
- Since they are massive they will transfer energy much more efficiently to nuclei than to electrons.
- Therefore the experimental signature is a low-energy (few keV to few tens of keV) nuclear recoil.
  - The main backgrounds at these low energies are radioactive decays, either intrinsic to the material or cosmogenic.
  - Many of these are β or γ decays which produce electron recoils, so being able to distinguish electron and nuclear recoils is a big advantage.

Detection methods

9

Possible methods of detection:

- Ionisation
  - The recoiling nucleus ionises neighbouring atoms, and you collect (usually) the electrons.
- Scintillation
  - The recoiling nucleus excites neighbouring atoms, and they de-excite by scintillation.
- Heat
  - You detect the extra energy deposited in your target.

Technologies:

- The most sensitive detectors tend to read out two signals, to aid in rejecting electron recoils
  - Semiconductor bolometers (Ge, Si) read out ionisation and heat (phonons)
  - Scintillating bolometers ($CaWO_4$) read out light and heat
  - Noble liquid TPCs (LXe, LAr) read out light and ionisation
  - Bubble chambers (C_3F_8) read out heat and sound (for α rejection)

Typical result

10

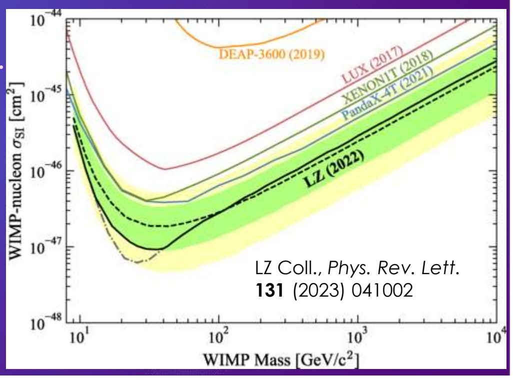
The recoil energy of a nucleus of mass M hit by a WIMP of mass m is

$$E = \frac{\mu^2 v^2}{M}(1 - \cos\theta),$$

where $\mu = mM/(m+M)$ is the reduced mass and θ is the scattering angle in the CM frame.

- For $m \ll M$, $E \propto m^2/M$, so lighter WIMPs give lower energy (potentially undetectable) recoils.
- For $m \gg M$, E is essentially independent of m and the event rate will depend on the number density of WIMPs, which is $\propto 1/m$.

This explains the shape of the limit curve.



LZ Coll., *Phys. Rev. Lett.* **131** (2023) 041002

Axions

11

The strong interaction is observed to conserve *CP* to very high precision, but in the Standard Model there is no reason for it to do so.

- Axion models introduce a new global symmetry which is spontaneously broken, dynamically relaxing the *CP* violating parameter to near zero.
  - The axion particle is the pseudo-Nambu-Goldstone boson of this field.

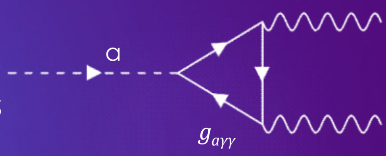
The axion mass is not predicted by the model. To make up the dark matter the standard QCD axion needs a mass of around 1 μeV to 1 meV.

- Despite this low mass, axions are cold dark matter because they are not produced thermally.

Detection of axions

12

The axion does not have conventional weak interactions, but it couples weakly to two photons via a triangle diagram.



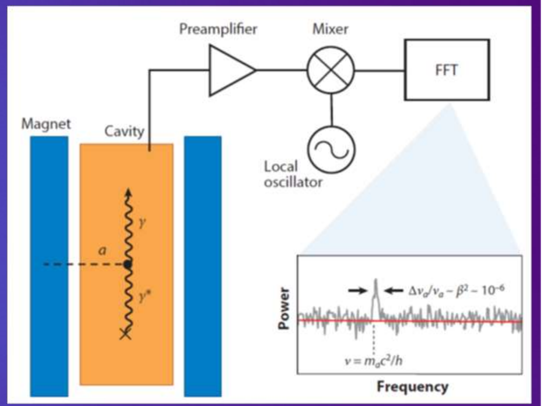
- Axions can therefore be converted to photons (and vice versa) in the presence of a magnetic field.
  - This is the basis of most axion detection methods.
  - As the axion de Broglie wavelength is extremely large, it can be treated classically as a wave.
- For the classic QCD axion, $m_a \propto g_{a\gamma\gamma}$ and there is a fairly narrow allowed band in parameter space.
  - However, axion-like particles (ALPs) with a wider range of properties occur in many BSM theories, so it is worth looking in other regions.

Microwave cavity axion detection

13

Axions in the Galactic halo would convert to photons in the microwave range.

- These can be searched for by immersing a resonant cavity in a strong magnetic field.
  - Axions with masses corresponding to the resonant frequency of the cavity would produce a small excess power, which is picked up by extremely sensitive electronics.
- The experiment has to scan over the mass range by adjusting its resonant frequency, which makes it very slow.



Graham et al., *Annu. Rev. Nucl. Part. Sci.* **65** (2015) 485

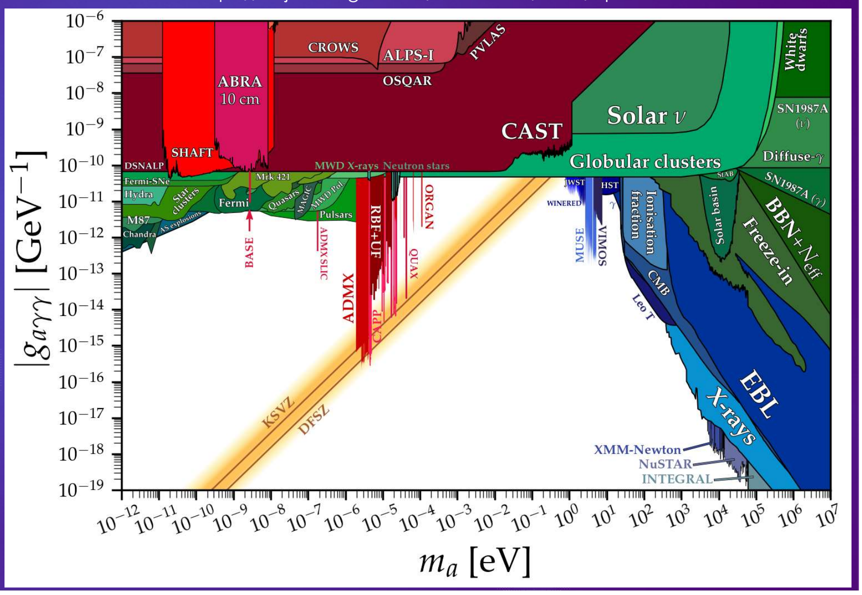
Limits on axions

14

So far the only experiments sensitive to the QCD axion in the mass range appropriate for dark matter are the microwave cavity experiments, known as ***haloscopes***.

Other experiments tend to be sensitive either to high masses or to large coupling constants.

https://cajohare.github.io/AxionLimits/docs/ap.html



Summary

15

Astrophysical evidence indicates that dark matter makes up about 84% of the matter in the Universe, is effectively stable, does not interact strongly or electromagnetically, and was non-relativistic at the time of structure formation.

- No Standard Model particle satisfies these criteria. However, many extensions to the Standard Model do predict something with appropriate properties.

The two most widely studied dark matter candidates are WIMPs (especially SUSY WIMPs) and axions.

- There are experimental searches ongoing for both of these, but no success so far.