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OVERVIEW OF ASYMMETRIC DARK MATTER

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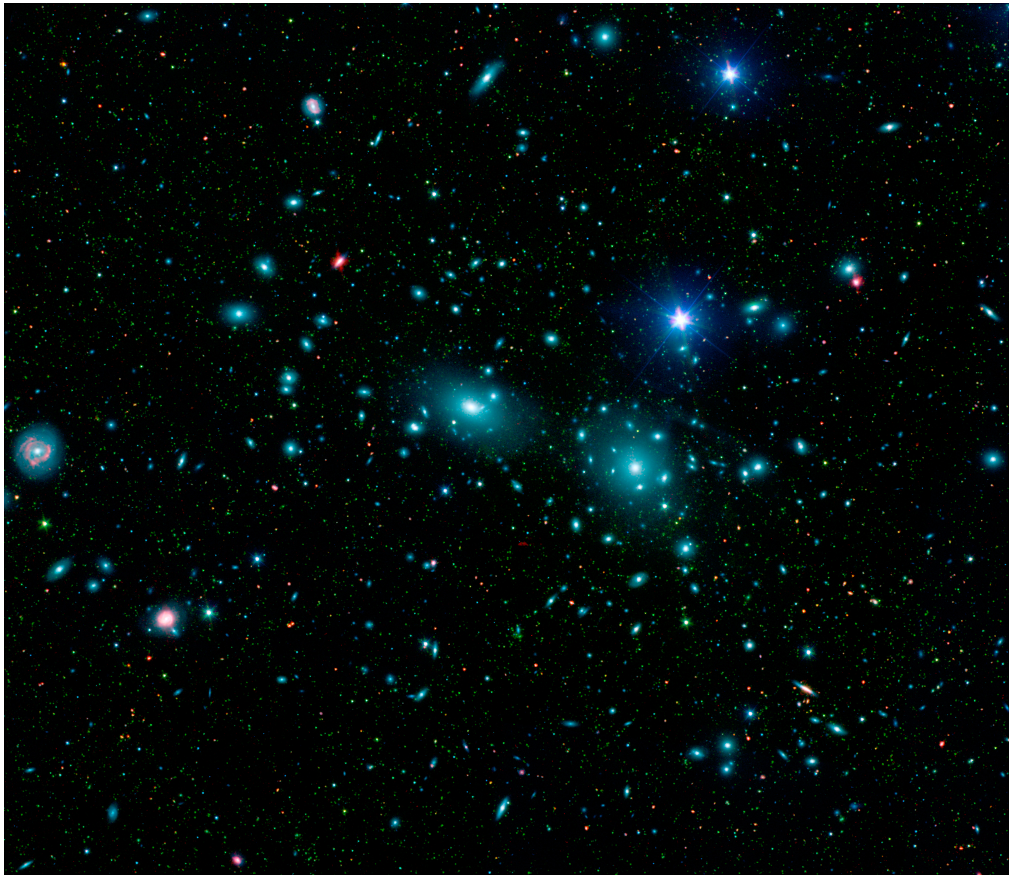
Based on IJMPA invited review:
K. Petraki and RV, arXiv:1305.4939

1. Dark matter exists!
2. WIMPs vs ADM vs sterile neutrinos vs axions
3. ADM generalities
4. Phenomenology
5. Final remarks

1. Dark matter exists!

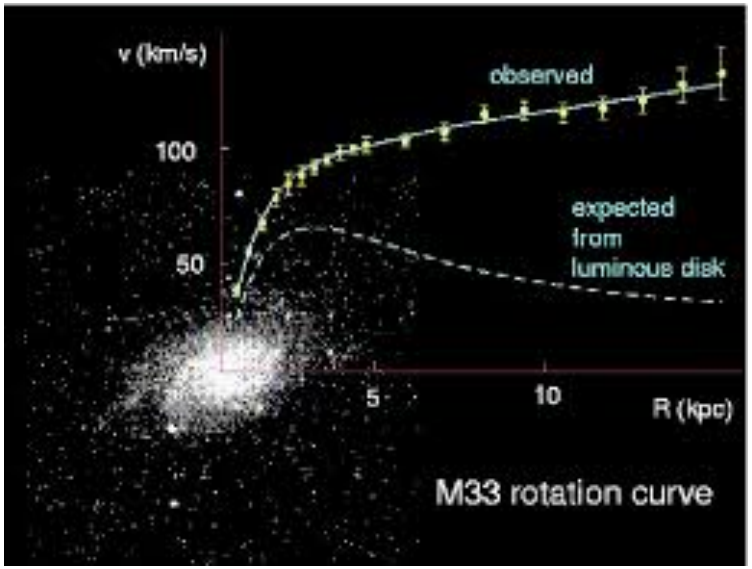
1937: Fred Zwicky inferred the existence of DM by analysing the velocity dispersion of galaxies in the Coma cluster.

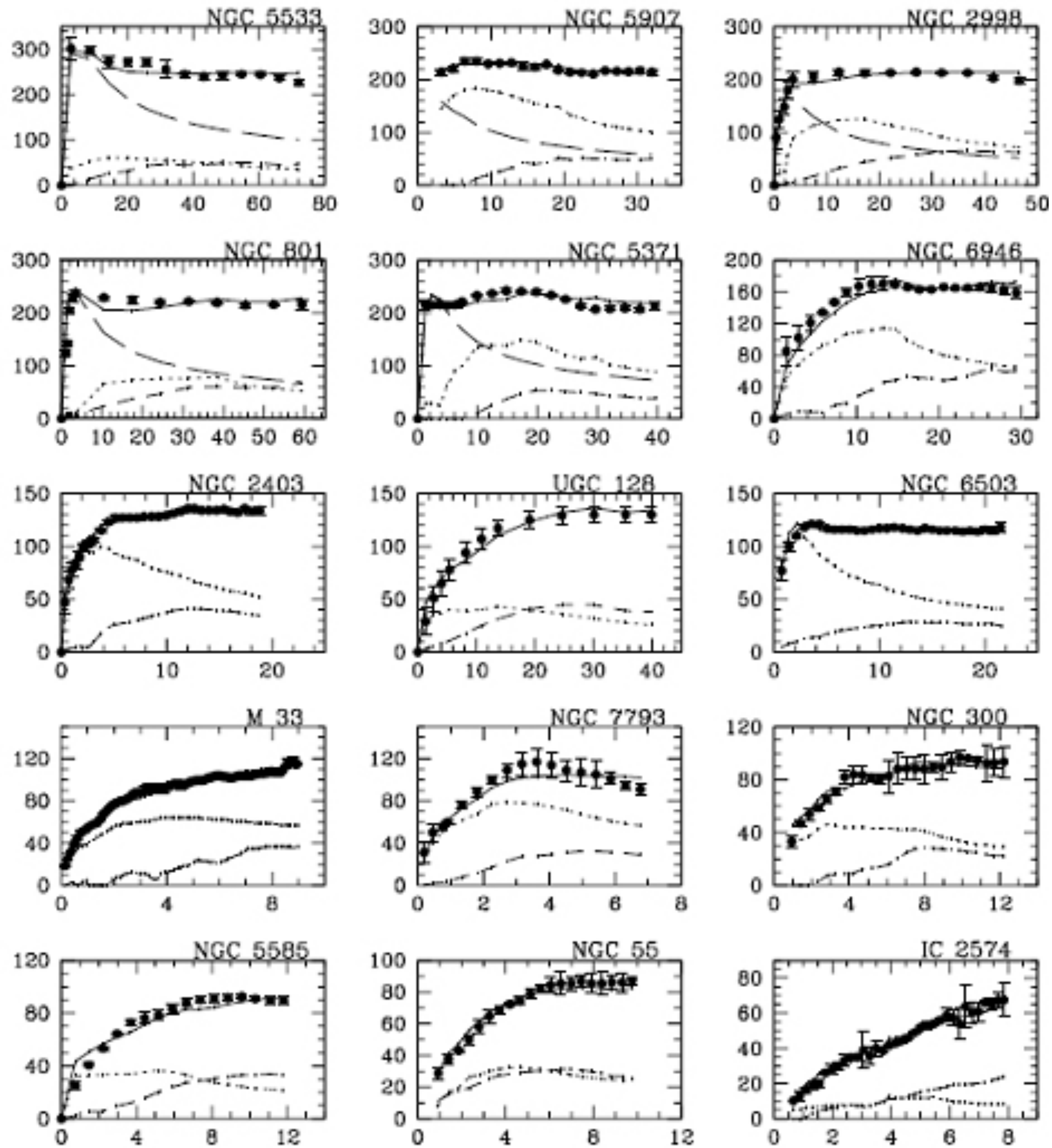


Galaxy rotation curves:

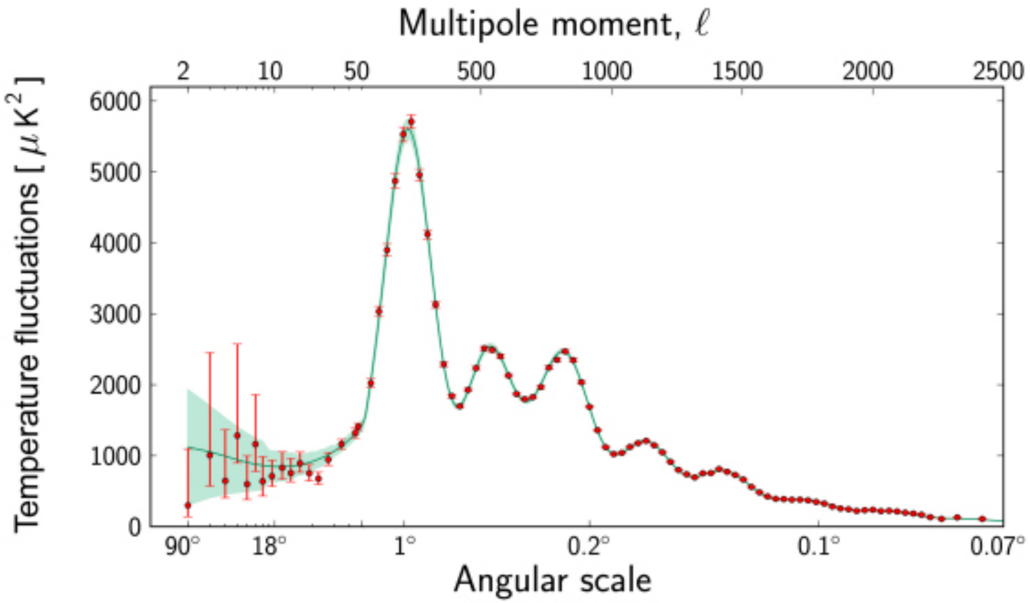
Babcock (1939) measured rotation curve of Andromeda concluding the mass to light ratio increases with radial distance, but attributed it to absorption of light.

Vera Rubin (1970) establishes flat rotation curves as evidence for DM forming galactic haloes.



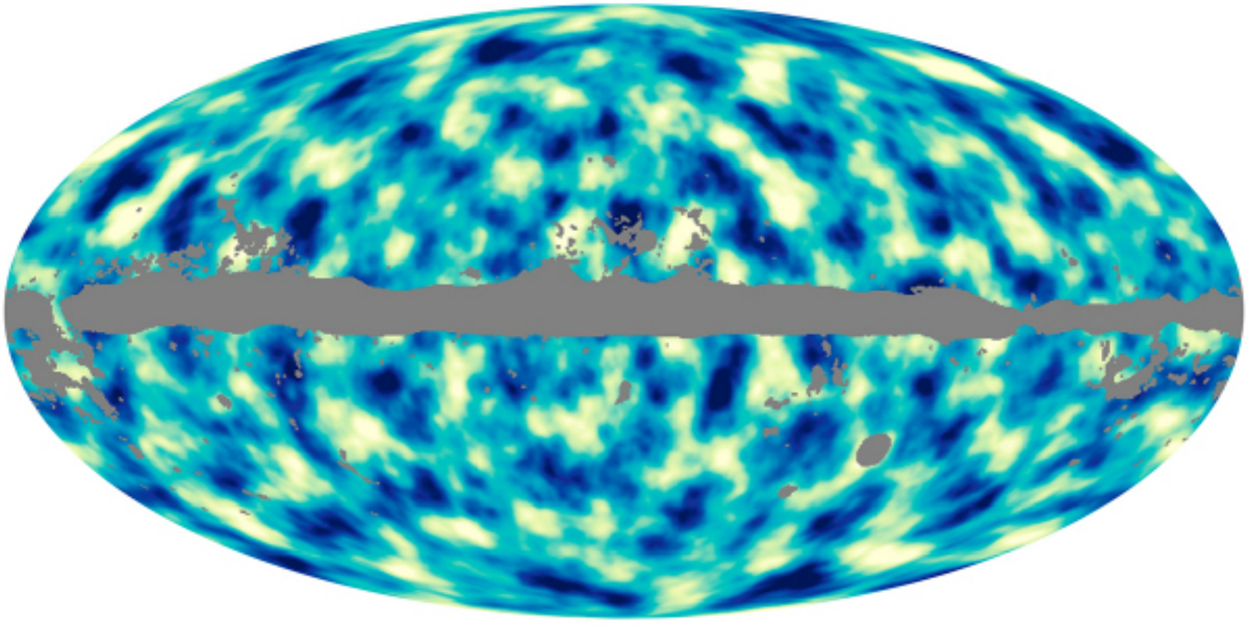

NGC 5533
NGC 5907
NGC 2998
NGC 801
NGC 5371
NGC 6946
NGC 2403
UGC 128
NGC 6503
M 33
NGC 7793
NGC 300
NGC 5585
NGC 55
IC 2574

CMB acoustic peaks and gravitational lensing:



Temperature anisotropy power spectrum from Planck.
1st peak = baryonic density
3rd peak = dark matter density

Planck all-sky map of DM distribution from gravitational lensing of CMB

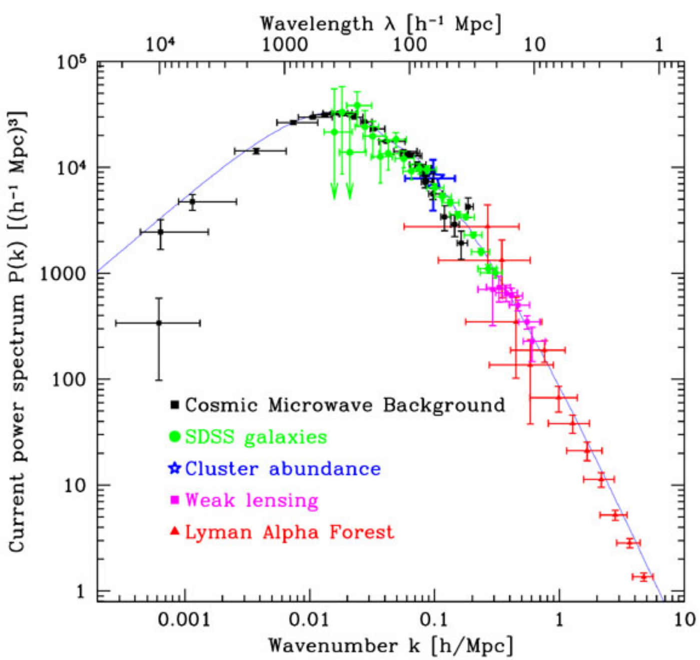


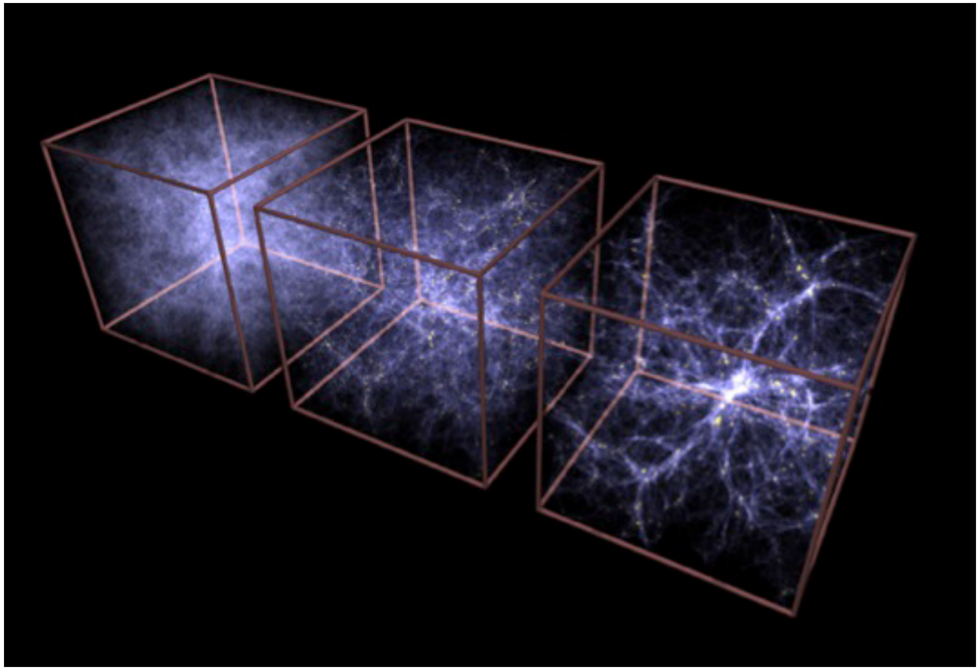
DM is need to explain large-scale structure formation:

Structure starts to grow through gravity in DM from the time of matter-radiation equality at z = 3000.

Baryonic matter feels the DM gravitational potential wells at z=1100 after photon decoupling.

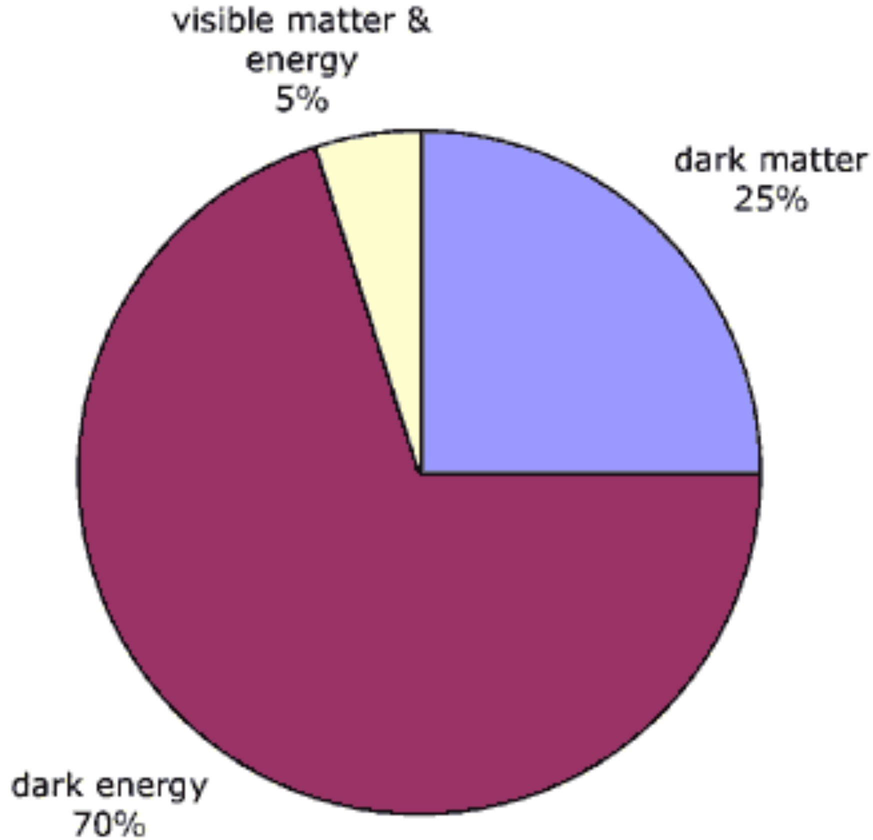
Without DM, structure formation begins too late to explain observations.





Bullet cluster:

Composition of the Universe, by percent

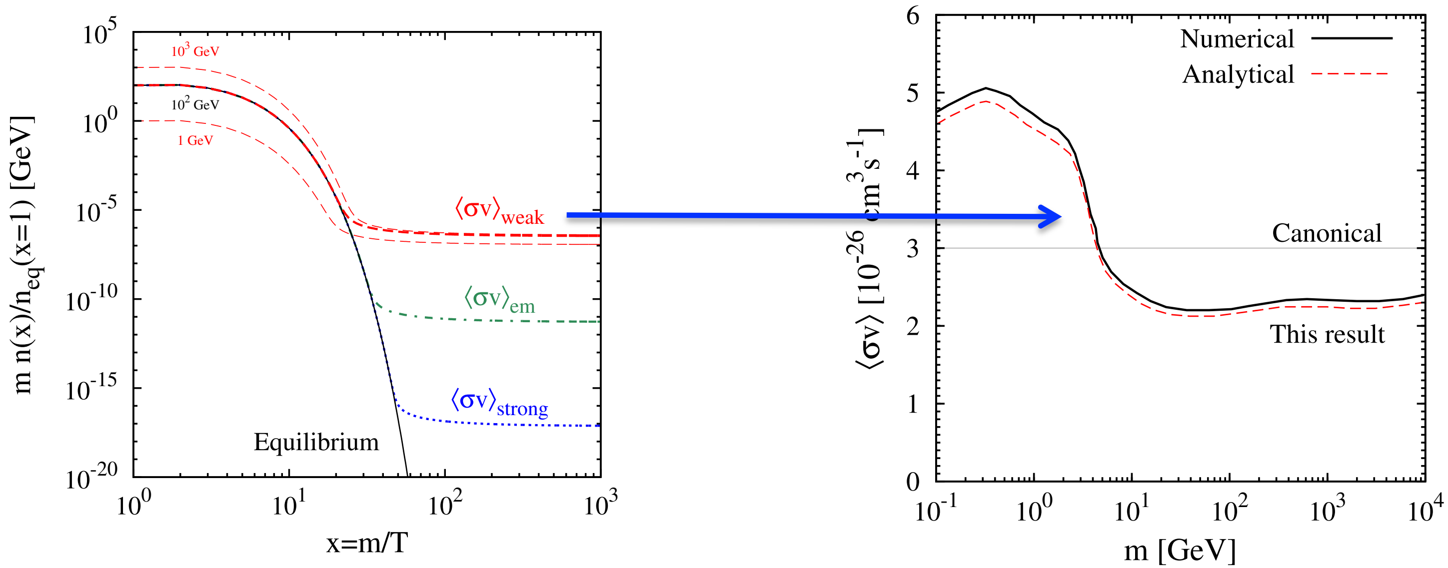


2. WIMPs vs asymmetric DM vs sterile neutrinos vs axions

Weakly Interacting Massive Particles:

The WIMP "miracle" can explain the observed DM density.
Connected to new weak/TeV scale physics e.g. susy.

WIMP decouples from the thermal plasma when non-relativistic and Boltzmann suppressed.



Steigman, Dasgupta, Beacom: Phys. Rev. D86 (2012) 023506

$$\Omega_\chi = \frac{m_\chi n_\chi}{\rho_c} \simeq \frac{6 \times 10^{-27}\ \mathrm{cm^3 s^{-1}}}{\langle \sigma_A v \rangle}$$

$$\simeq 0.2 \text{ for } \langle \sigma v \rangle \simeq 3 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$$

Asymmetric Dark Matter:

Why is $\Omega_d \approx 5\Omega_v$?

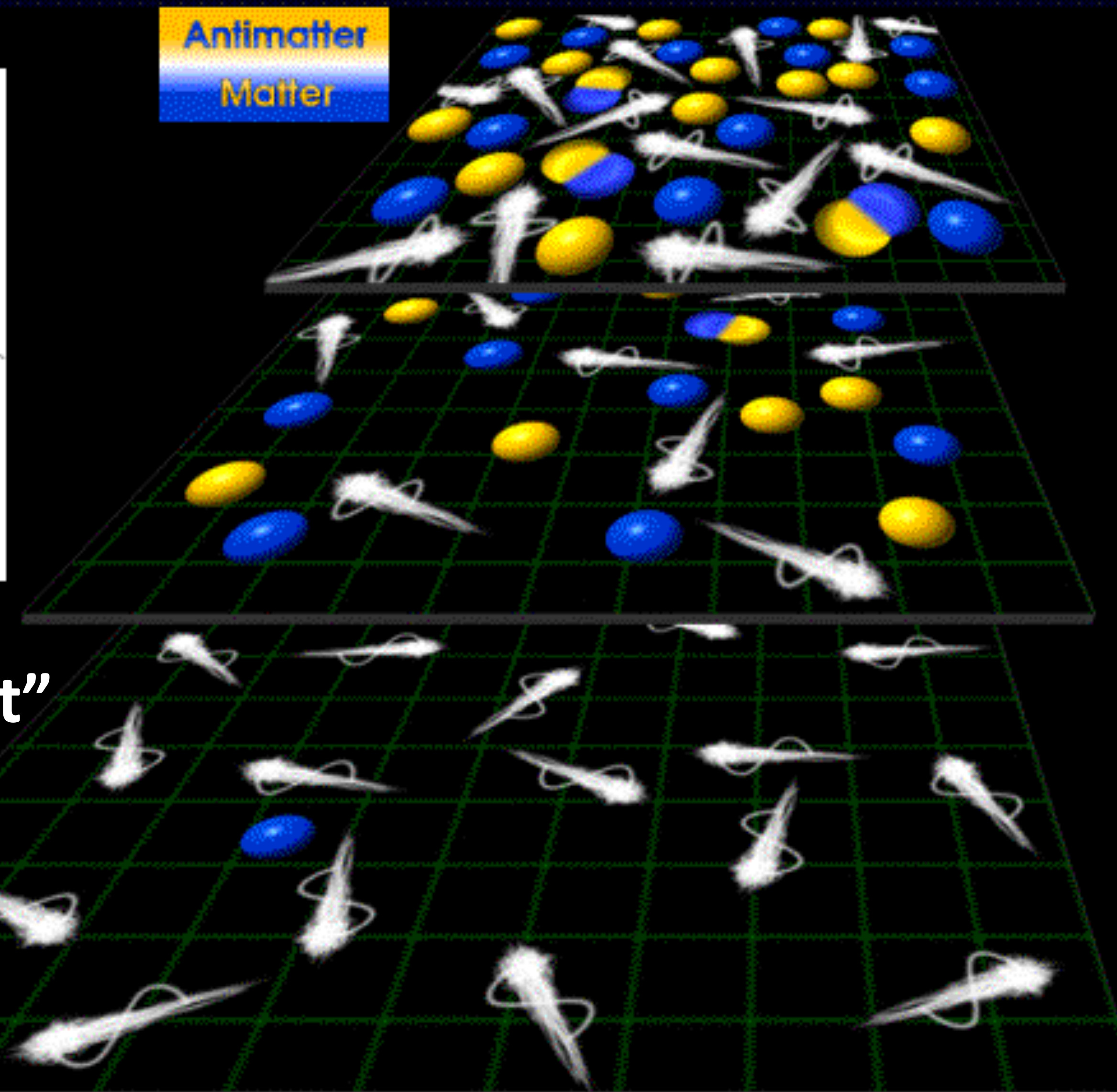
The WIMP miracle requires this similarity to be a coincidence.

Ω_v is due to a particle-antiparticle asymmetry, not the non-relativistic decoupling of a self-conjugate or symmetric relic.

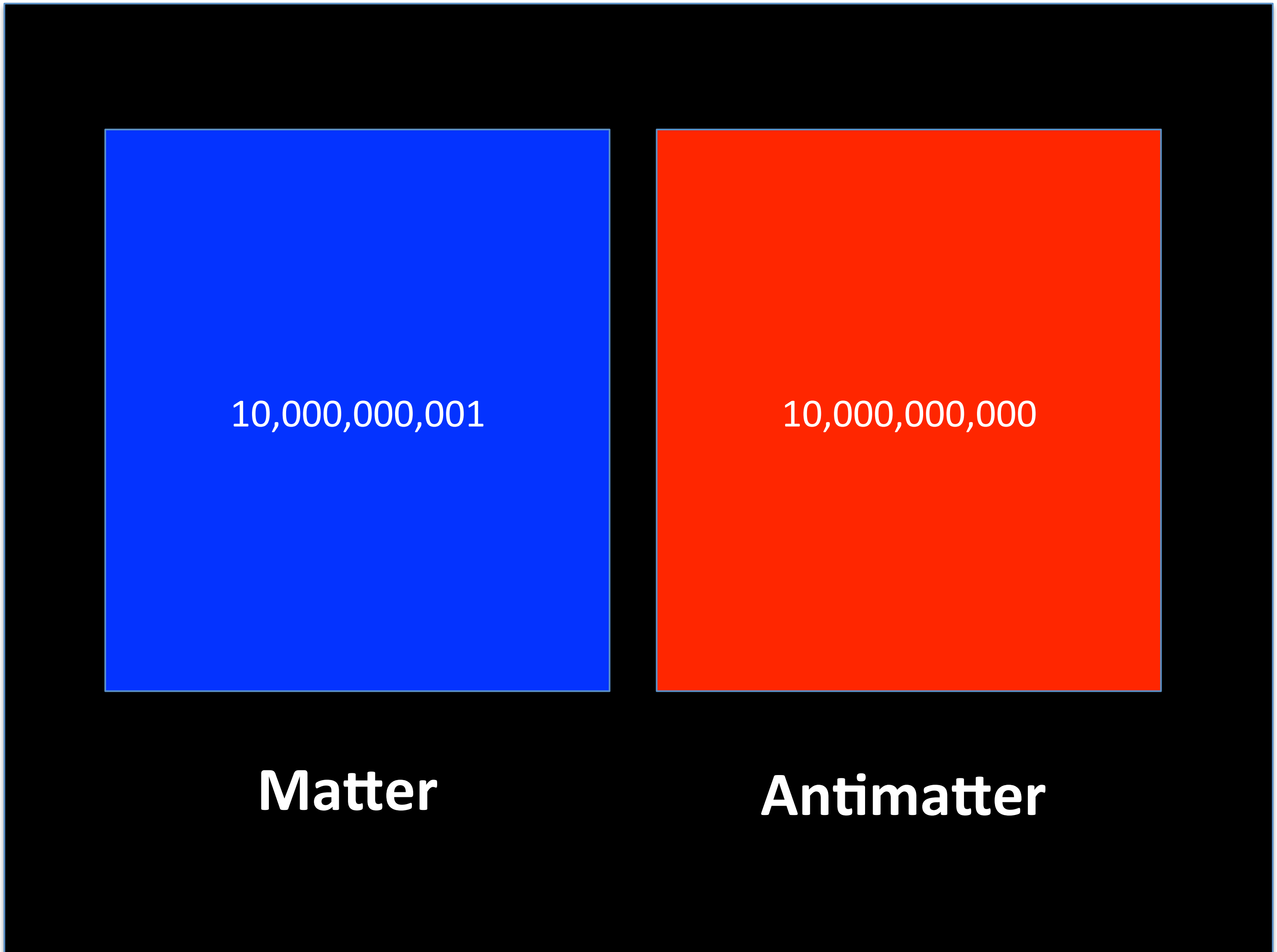
Motivates "asymmetric dark matter (ADM)":
DM and VM densities both due to related particle-number asymmetries.

DM mass scale typically few to 10s of GeV range.

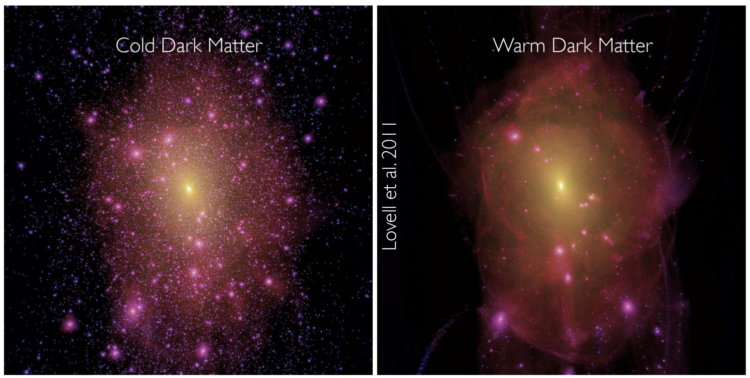
Matter-Antimatter Asymmetry of the Universe



The "symmetric part" annihilates into radiation, excess matter left as relic.


10,000,000,001
10,000,000,000
Matter
Antimatter

warm, cool, chilled: small-scale structure problem?



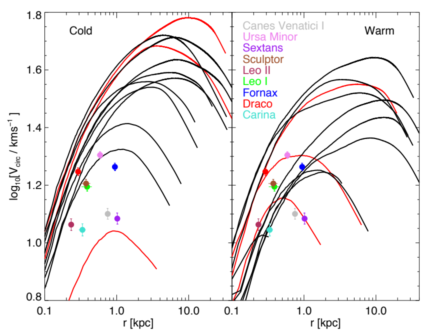


Figure 5. Circular velocity curves for the 12 CDM (left) and WDM (right) subhaloes that had the most massive progenitors. The 3 red curves represent subhaloes with the most massive progenitors, which could correspond to those currently hosting counterparts of the LMC, SMC and the Sagittarius dwarf. The 9 black curves might more fairly be compared with the data for the 9 bright dwarf spheroidal galaxies of the Milky Way considered by Wolf et al. (2010). Deprojected half-light radii and their corresponding half-light masses, as determined by Wolf et al. (2010) from line-of-sight velocity measurements, are used to derive the half-light circular velocities of each dwarf spheroidal. These velocities and radii are shown as coloured points. The legend indicates the colour coding of the different galaxies.

From Lovell et al: MNRAS 420, 231 (2012)

Sterile neutrinos:

Simply add RH Majorana neutrinos to minimal SM!

EeV

PeV

TeV

Electroweak scale

GeV

RHν

MeV

warm DM → N_1

keV

Original idea: Dodelson & Widrow PRL 72 (1993) 17

Shi, Fuller: PRL 82 (1999) 2832
Kusenko, Petraki: Phys Rev D77 (2008) 065014
Canetti, Drewes, Frossard, Shaposhnikov: arXiv:1208.4607

eV

LHν

Axions:

Strong CP problem.

$$\mathcal{L}_{\rm QCD} \supset \theta \; {\rm Tr}(G^{\mu\nu}\tilde{G}_{\mu\nu})$$

Neutron EDM bound $\theta < 10^{-10}$

Peccei-Quinn solution turns θ into a field: implies very light pseudoscalar boson, the axion.

Perfectly legitimate candidate – but the strong CP problem can be solved without axions being a dominant component of DM.

3. ADM GENERALITIES

In ADM models:

- the "visible sector" is the SM or some extension
- the "dark sector" may be some other gauge theory

$$G = G_V \times G_D \times G_{V+D}$$

or otherwise just fermions and/or scalars.

The sectors are coupled in the very early universe, and the asymmetries get related.

The sectors then decouple at low energies.

In most models the VM & DM number densities are similar, so the dark sector has to contain a stable GeV-scale particle.

See later comment on alternate mass scale possibility

What stabilises massive particles? In the SM:

proton (antiproton) = lightest particle carrying conserved baryon number
electron (positron) = lightest particle carrying conserved electric charge
lightest neutrino = lightest half-integer spin particle (angular mom. conservation)
neutrons in appropriate nuclei = bound state effect

We hypothesise at least a "dark baryon number B_D".

**Some models have a "dark EM" and hence dark radiation.
Some interaction has to "annihilate the symmetric part".
If not dark EM, then something else, e.g. Yukawa mediated annihilation into dark massless fermions. And so on.**

N_{eff} is an important constraint: discuss later.

3.1 Symmetry structure

Dark sector: B_D (analogue of visible baryon number B_V). The asymmetry in the dark sector is in B_D.

Visible sector: best to consider $(B\text{-}L)_V$, because it is anomaly-free, and above the EW phase transition we have to take into account sphaleron reprocessing. E.g. we can have the initial visible-sector asymmetry purely in lepton number.

Asymmetry: $$\eta(X) \equiv \sum_i X_i (n_i - n_{\bar{i}})/s$$

Case 1: Baryon-symmetric universe

Dodelson and Widrow: PRL 64 (1990) 340
Davoudiasl et al: PRL 105 (2010) 211304
Bell, Petraki, Shoemaker, RV: PRD 84 (2011) 123505
Cheung, Zurek: PRD 84 (2011) 035007
von Harling, Petraki, RV: JCAP 1205 (2012) 021
others … see 1305.4939 for full reference list.

Conserved: $$B_{\rm con} \equiv (B-L)_V - B_D$$

Broken: $$B_{\rm bro} \equiv (B-L)_V + B_D$$

At early times and high temperatures: **B_{bro} violated** but **B_{con} strictly conserved.**

At late times and low temperatures, B_V and B_D are separately conserved – ensures stability of protons and DM.

Generate B_{bro} asymmetry using dynamics obeying Sakharov conditions. Then

$$\eta((B-L)_V) = \eta(B_D) = \eta(B_{\rm bro})/2$$

The B-L number of VM is secretly cancelled by the DM!

Simultaneous creation of correlated asymmetries.
"Pangenesis" "Cogenesis"

$$\eta((B-L)_V) = \eta(B_{\mathrm{bro}})/2$$

VISIBLE SECTOR

$$\eta(B_D) = \eta(B_{\mathrm{bro}})/2$$

DARK SECTOR

Case 2: visible to dark reprocessing

Initially, $(B\text{-}L)_V$ is broken but B_D is not.

asymmetry created here

During the chemical equilibration, some non-trivial combination of $(B\text{-}L)_V$ and B_D is conserved.

The sectors subsequently decouple.

$$\eta((B-L)_V) \neq 0$$

VISIBLE SECTOR

shared s.t.

$$\eta((B-L)_V) \sim \eta(B_D)$$

$$\eta(B_D) \neq 0$$

DARK SECTOR

Case 3: dark to visible reprocessing

Initially, B_D is broken but $(B\text{-}L)_V$ is not.

During the chemical equilibration, some non-trivial combination of $(B\text{-}L)_V$ and B_D is conserved.

The sectors subsequently decouple.

asymmetry created here

$$\eta(B_D) \neq 0$$

DARK SECTOR

shared s.t.

$$\eta((B-L)_V) \sim \eta(B_D)$$

$$\eta((B-L)_V) \neq 0$$

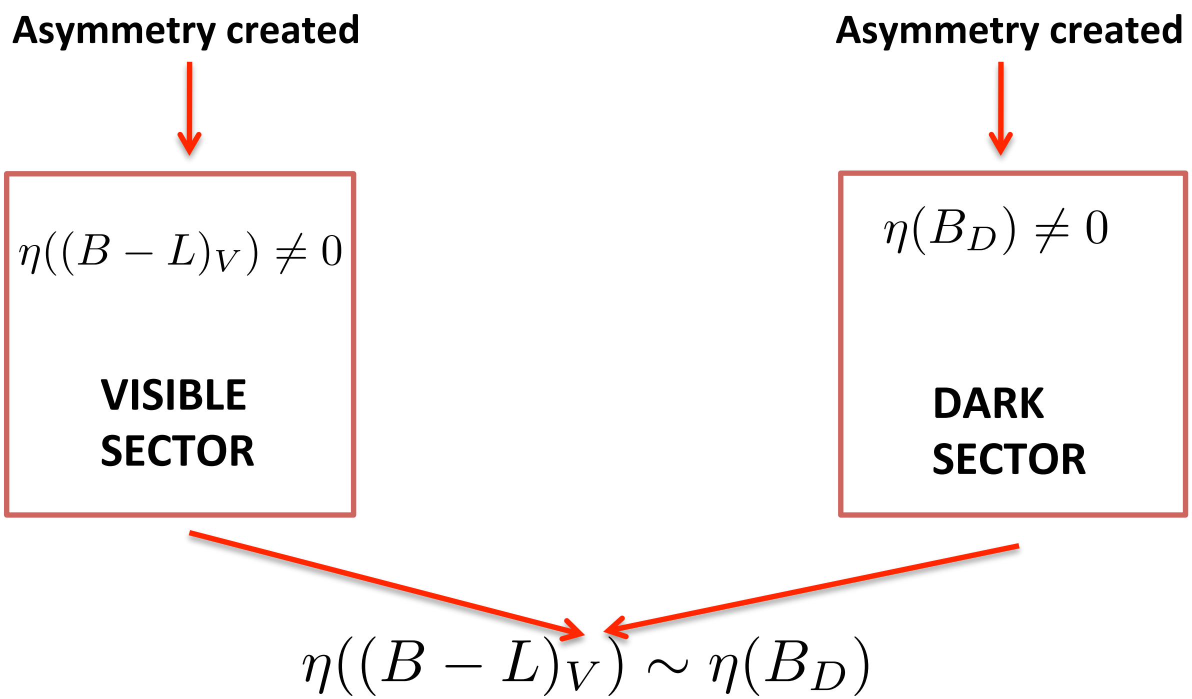
VISIBLE SECTOR

Case 4: initial asymmetries develop independently

Initially, both $(B\text{-}L)_V$ and B_D are broken.

To relate the asymmetries, subsequent interactions should preserve some non-trivial combination of $(B\text{-}L)_V$ and B_D.

The sectors subsequently decouple.



One version of mirror DM cosmology: sectors remain decoupled: different T, but identical microphysics!

3.2 Asymmetry generation

Creating an asymmetry (Sakharov 1967):

1. **Violation of particle number conservation**
2. **C and CP violation**
3. **Out-of-equilibrium process**

1. **Obvious**

2. $\text{Rate } i \to f(\Delta B = b) \neq \text{Rate } \bar{i} \to \bar{f}(\Delta B = -b)$

3. $\text{Rate } i \to f(\Delta B = b) \neq \text{Rate } f \to i(\Delta B = -b)$

Common general mechanisms:

Out-of-equilibrium decays of heavy particles:

$$\Gamma(\psi \to x_1 \ x_2 \ldots) \neq \Gamma(\psi \to x_1^* \ x_2^* \ldots)$$

Affleck-Dine: production of charged scalar condensate through time-dep. phase.
Supersymmetry, uses flat directions.

First-order phase transition: nucleation of bubbles of true vacuum, sphalerons,
CP-violating collisions with bubble walls.

Asymmetric freeze-out: DM particles coannihilate with SM particles at a
different rate from DM antiparticles.

Asymmetric thermal production (asymmetric freeze-in): DM and anti-DM
never in thermal equilibrium; slowly produced at different rates.

Spontaneous genesis: Sakharov conditions presuppose CPT invariance.
Expanding universe induces effective CPT violation.
Asymmetry generation in eq. without C, CP violation.

3.3 Dark interactions

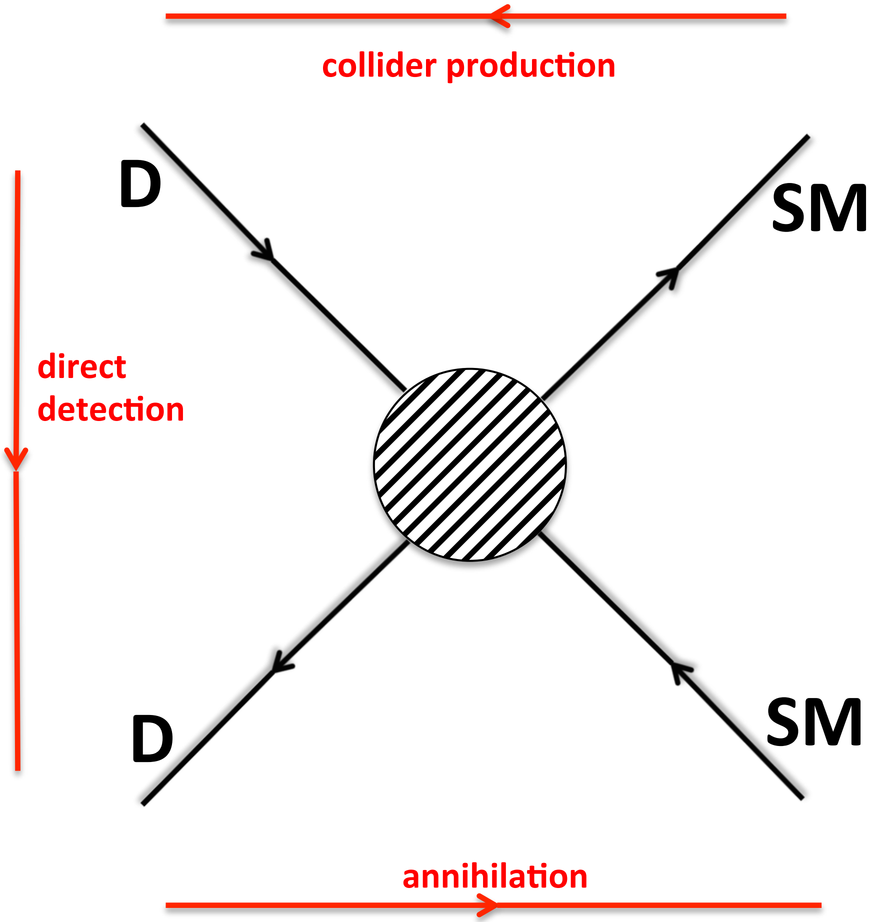
A logical and elegant possibility is that the symmetric part annihilates into light dark-sector states – dark radiation – to parallel what happens in the visible sector.

There are many microphysical possibilities. Main constraint is N_{eff} (see later).

A simple, elegant possibility is an unbroken dark U(1) force – dark EM. Dark-charge neutrality => at least two oppositely charged dark species, plasma ionised or in neutral dark atoms. Direct-detection prospects through kinetic mixing with usual photon.

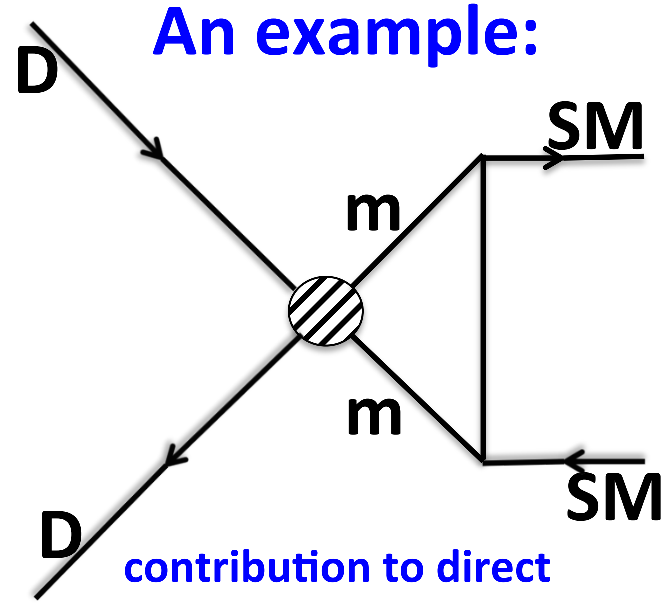
A variant on dark EM has U(1) spontaneously broken and dark photon massive, but lighter than the DM. The symmetric part can annihilate into dark photons which, through kinetic mixing, subsequently decay into, say, e^+e^-.

Annihilating the symmetric part without dark radiation:

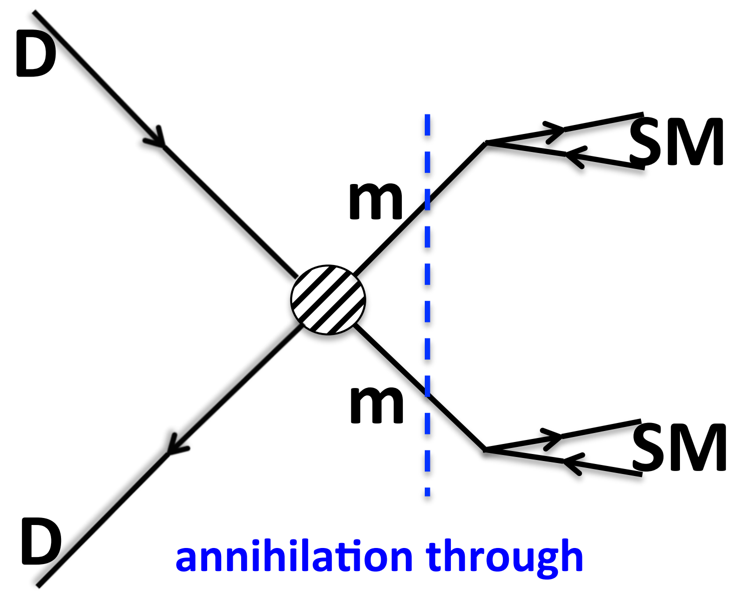


Direct annihilation to SM particles constrained by direct detection and colliders. Role for flavour/Lorentz structure.

An example:



contribution to direct detection through loop



annihilation through on-shell unstable mediator

Bai et al: JHEP 1012 (2010) 048; Buckley: PRD 84 (2011) 043510; Fox et al: PRD86 (2012) 015010; March-Russell et al: 1203:4854

3.4 Dark matter mass scale

The few-GeV scale arises when the asymmetry transfer or simultaneous genesis interactions decouple while the DM particle is relativistic.

Alternative: the decoupling temperature is of order the DM mass, but somewhat smaller. Then the DM particle is starting to become Boltzmann suppressed as the transfer stops. The DM number density is lower, and hence the mass scale must be higher e.g. weak scale, or RH breaking scale, etc.

DM mass scale ~ (5 – 10) x transfer decoupling temperature.

See e.g. Barr, Chivukula, Farhi: PLB241 (1990) 387.
Cohen, Zurek: PRL 104 (2010) 101301
Buckley, Randall: JHEP 1109 (2011) 009

Focus on the more common few-GeV scale case here. For ADM to be really compelling, need good reason for this mass scale.

The DM mass you need depends on the ADM model.

Baryon-symmetric models: $$m_{\rm DM} \simeq q_{\rm DM} \times (1.6 - 5)\ {\rm GeV}$$

q_{DM} = baryonic charge of DM

Other cases: depends on details of the chemical equilibrium.

One special case (single dark baryon species, relativistic decoupling):

$$m_{\rm DM} \simeq q_{\rm DM}^{-1} \times (5 - 7)\ {\rm GeV}$$

Ibe et al PLB708, 112 (2012)

Ideas: (1) m_{DM} ~ QCD scale, e.g. mirror DM
(2) m_{DM} = (λ~10^{-2}) x m_{EW}
(3) hidden sector → visible sector → dark sector

Recipe for ADM model building:

- Choose case 1, 2, 3 or 4 and specify the visible-dark interactions
- Choose an asymmetry-generating dynamics
- Define the internal microphysics of the dark sector
- Explain how the symmetric dark component is annihilated
- Make sure no astro/cosmo/particle constraints are violated

Many papers do not specify all of these elements

4. PHENOMENOLOGY

The dark sectors of ADM models are rich and interesting!

Extreme example: mirror matter i.e. exactly isomorphic to SM

(Blinnikov&Khlopov; Foot, Lew, RV, …)

Generic possible features:

- multi-component
- dark electromagnetism & dark "atoms"
- dark radiation, dark "neutrinos"
- mediator sector
- common extra Z-boson
- Higgs boson mixing
- self-interacting at some level

Generic constraints:

- extra radiation at BBN/recomb. (Planck!)
- self-interactions from triaxiality of DM haloes of elliptical galaxies, and clusters (Bullet etc.)
- direct detection (Z', kinetic mixing, …)
- collider (Higgs mixing, Z', monojets, …)
- Capture in stars

Key questions:

Does ADM phenomenology *have* to be unconventional? NO.

But it is very interesting that generically it *is* unconventional.

How different from standard *should* DM properties be?
Does ADM provide a new paradigm to solve the DM problems?

Extra radiation:

Entropy conservation:

$$\frac{g_{\rm V} T_{\rm V}^3}{g_{\rm D} T_{\rm D}^3} = \frac{g_{\rm V,dec}}{g_{\rm D,dec}}$$

implies:

$$g_{\rm D,dec} \lesssim 18 \left(\frac{g_{\rm D}}{2}\right)^{1/4} \left(\frac{g_{\rm V,dec}}{106.75}\right) (\Delta N_{\rm eff})^{3/4}$$

where:

$$\Delta\rho = \frac{7\pi^2}{120} \left(\frac{4}{11}\right)^{4/3} \Delta N_{\rm eff}\, T_{\rm V}^4$$

BBN allows $\Delta N_{eff} \leq 1$.

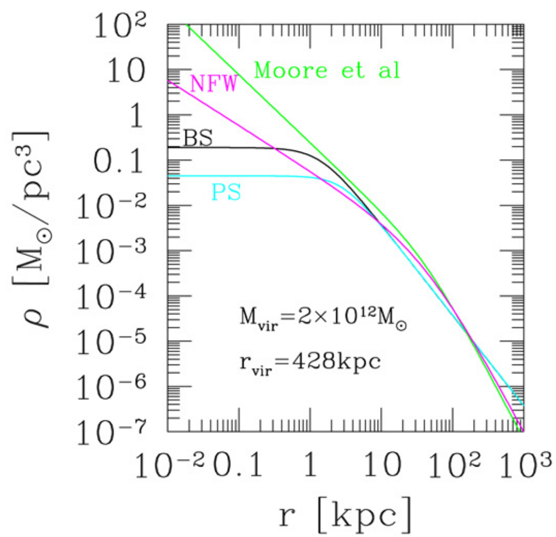
Various CMB/BAO combinations @ 95% C.L. give
$-0.3 < \Delta N_{eff} < 1$

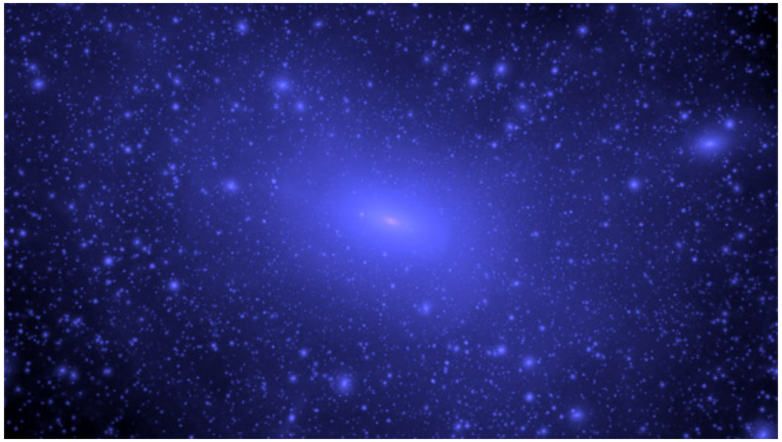
Structure formation and galactic dynamics:

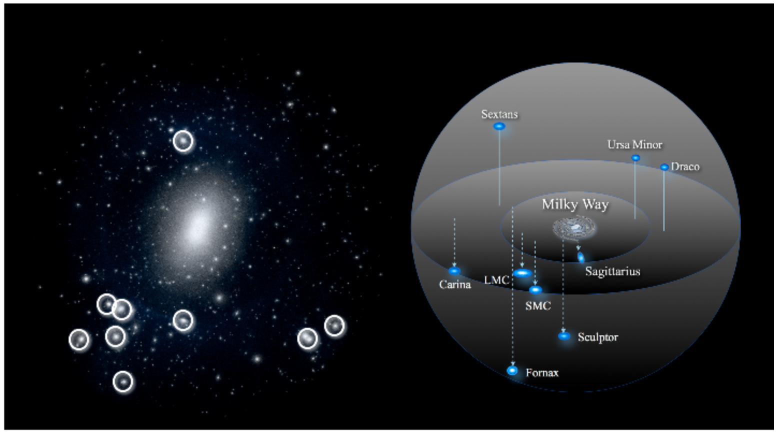
galactic and sub-galactic problems:

- cores vs cusps
- missing satellites
- "too big to fail"
- co-rotating plane of satellites

small-scale structure wash out; self-interacting DM







constraints:
- triaxiality of DM haloes around elliptical galaxies
- Bullet cluster

} bounds on DM self-ints.

Ingredients for a solution:
- late DM decoupling from dark radiation (Silk damping, acoustic oscillation damping)
- v-indep. self-int. Xsection: near 0.6 cm^2/g
- v-dep. self-int. Xsection: can resolve sub-gal. problems but maintain triaxiality

Direct detection:

Possible ADM-nucleon interactions: Z' coupled to anomaly-free B_{con}
Dark-photon kinetic mixing with photon
Dark-visible Higgs mixing

$$\sigma^{SI}_{B_{con}} \simeq (10^{-46}\mathrm{cm}^2)\, q^2_{\mathrm{DM}} \left(\frac{g}{0.1}\right)^4 \left(\frac{3\ \mathrm{TeV}}{M}\right)^4$$

g, M = Z' coupling, mass

Short range

$$\sigma^{SI}_{D} \simeq (10^{-40}\mathrm{cm}^2) \left(\frac{\epsilon}{10^{-4}}\right)^2 \left(\frac{g_D}{0.1}\right)^2 \left(\frac{1\ \mathrm{GeV}}{M_D}\right)^4$$

kinetic mixing ε
dark-photon coupling, mass = g_D, M_D

(Both evaluated for m_{DM} = 5 GeV.)

The kinetic-mixing case can give a cross-section large enough to be roughly compatible with DAMA, CoGeNT, CRESST and CDMS; mutual compatibility is not perfect, and there is tension with XENON. LUX is a problem …

By varying parameters, can easily be small enough to satisfy XENON bound.

Long range

Mirror DM with massless mirror photon

Foot: PRD69 (2004) 036001; D82 (2010) 095001; PLB703 (2011) 7; 1305.4316

General hidden-sector DM with massless dark photon

Foot: 1209.5602

Multi-component ionised DM, masses m_i.
Massless mirror/dark-photon interactions thermalise the species,
to give mass-dependent velocity dispersions:

$$v_i \simeq v_{\rm rot} \left(\frac{\bar{m}}{m_i}\right)^{1/2} \qquad \bar{m} \equiv \Sigma_j n_j m_j / \Sigma_j n_j$$

Most massive states, e.g. mirror Fe, give largest signal if abundant enough.
They also have the smallest velocity dispersions: tail of distribution shorter.
This can partially explain why the higher-threshold XENON expt. has no signal
while lower-threshold expts. have signals.

Interplay b/w m_i-dep vel. disp. and long-range DM-nucleon microscopic
interaction can bring DAMA, CoGeNT, CRESST-II into good agreement.
Still some tension with XENON100. LUX is a problem …

Single-species DM with light but not massless mediator φ:
m_φ~10 MeV for m_{DM}~10 GeV preferred.

Fornengo, Panci, Regis: PRD84 (2011) 115002

Capture in stars:

- No annihilations means DM can accumulate in stars (losses can occur through co-annihilations and evaporation).
- In the Sun and main-sequence stars: can alter helioseismology and neutrino fluxes through energy transport due to DM-nucleus scattering.
- Fermionic ADM can exceed Chandrasekhar limit in a neutron star, thus form black hole and consume it. Old NS => bounds.
- Bosonic ADM can do the same, but bounds very sensitive to inevitable DM self-interactions. In many cases, there are no meaningful bounds.

Collider signatures

(i) Z' decays to the dark sector:

Gauged $B_{\rm con} = (B-L)_V - B_D$

Invisible width due to Z' decays to dark-sector particles and neutrinos.
p p → ZZ' → $l^+ l^-$ (or γ) + missing E_T.
Get coupling to neutrinos from Drell-Yan and use of weak-isospin invariance.
Thus measure non-neutrino invisible width.

Petriello et al: PRD77 (2008) 115020; Gershtein et al: PRD78 (2008) 095002

(ii) Monojets (hylogenesis example):

Davoudiasl et al: PRD84 (2011) 096008

$$\frac{1}{\Lambda^3}\,\overline{(u_R)^c}\,d_R\,\overline{(d_R)^c}\,\Psi_R\,\Phi + H.c. \;\Rightarrow\; qq' \longrightarrow \bar{q}\bar{\Psi}\Phi^*$$

Ψ, Φ dark-sector species

Monojet cross-section sensitivity to about 7 fb with 100 fb^{-1} at 14 TeV LHC.
Probe few-TeV scale of new physics.

5. FINAL REMARKS

- Why is $\Omega_d \approx 5\Omega_v$? This smells like an important clue as to the nature of DM.
- ADM allows the dark sector to have rich physics.
- Many models have been proposed.
- ADM can have the right stuff to solve the small-scale structure problems.
- Can help reconcile the direct-detection experimental results.

To reiterate:

Does ADM phenomenology *have* to be unconventional? NO.

But it is very interesting that generically it *is* unconventional.

How different from standard *should* DM properties be?
Does ADM provide a new paradigm to solve the DM problems?