Hunting for dark matter in the forest (astrophysical constraints on warm dark matter)

Tom Theuns
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with the Eagle collaboration: J Schaye (Leiden), R Crain (Liverpool), R Bower, C Frenk, & M Schaller (ICC) and A Garzilli (Leiden), A Boyarsky (Leiden)
Contents:

• Dark matter: what is it, where is it, do we need it? How much?
• Dark matter: what do we need from it? Cold dark matter!
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• Interlude: quasar spectra
• Dark matter: cut-off in flux power spectra: WDM or thermal
• Future: lensing, and Relhics
The Dark Matter Rap: *Cosmological History for the MTV Generation*
by David Weinberg

My name is Fritz Zwicky,
I can be kind of prickly,
This song had better start
by giving me priority.
Whatever anybody says,
I said in 1933.
Observe the Coma cluster;
the redshifts of the galaxies
imply some big velocities.
They're moving so fast,
there must be missing mass!
Dark matter.

Dark matter: Do we need it? What is it? Where is it? How much?
Do we need it? Do we need it? Do we need it? Do we need it?
Dark matter: Do we need it? What is it? Where is it? How much?

Cosmological History for the Twitter Generation

Galaxies and how they are distributed in the Universe require the existence of mass that does not shine. The nature of this dark matter is presently unknown.

\[ V^2 = \frac{GM}{R} \]
Planck CMB map ($z=1000$)

linear growth: $\delta \propto \frac{1}{1+z}$

CfA map of galaxies ($z=0$)
Galaxy clustering: SDSS
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Millennium Simulation
10,077,696,000 particles

(\(z = 0\))  movie Volker Springel
Galaxy stellar mass function versus dark matter halo mass function

Dark halos (const M/L)

galaxies

Stellar Mass

Halo Mass

Bower+06
Galaxy formation efficiency

Stellar mass / halo mass

halo mass / solar mass
The EAGLE project: Simulating the evolution and assembly of galaxies and their environments

Joop Schaye,1* Robert A. Crain,1 Richard G. Bower,2 Michelle Furlong,2 Matthieu Schaller,2 Tom Theuns,2,3 Claudio Dalla Vecchia,4,5 Carlos S. Frenk,2 I. G. McCarthy,6 John C. Helly,2 Adrian Jenkins,2 Y. M. Rosas-Guevara,2 Simon D. M. White,7 Maarten Baes,8 C. M. Booth,1,9 Peter Camps,8 Julio F. Navarro,10 Yan Qu,2 Alireza Rahmati,7 Till Sawala,2 Peter A. Thomas,11 James Trayford2

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• 1504\(^3\) Gadget 3 simulation
• (100 Mpc)\(^3\) volume
• baryonic mass \(10^6\ M_{\text{sun}}\)
• Calibrated to \(z=0\) stellar MF
• Local subgrid physics
Dark matter: what do we need from it?

non-baryonic, small cross section, does not radiate (much): how about neutrinos?

actually: that won’t make galaxies!
The cold dark matter power spectrum

... as computed by Bond & Efstathiou '87

...and as measured by Planck
NFW profile:

\[ \rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, \]
Eagle

Schaller +15
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Three (four?) issues with CDM:

Discrepancies have emerged between the predictions of standard cold dark matter (CDM) theory and observations of clustering on subgalactic scales. Warm dark matter (WDM) is a simple modification of CDM in which the dark matter particles have initial velocities due either to their having decoupled as thermal relics or to their having been formed via nonequilibrium decay. We investigate the nonlinear gravitational clustering of WDM with a high-resolution $N$-body code and identify a number of distinctive observational signatures. Relative to CDM, halo concentrations and core densities are lowered, core radii are increased, and large halos emerge with far fewer low-mass satellites. The number of small halos is suppressed, and those present are formed by “top-down” fragmentation of caustics, as part of a “cosmic web” connecting massive halos. Few small halos form outside this web. If we identify small halos with dwarf galaxies, then their number, spatial distribution, and formation epoch appear in better agreement with the observations for WDM than they are for CDM.
All these can be solved be warm dark matter.

CDM  WDM
I “Observed voids are more empty than in cold dark matter”

(Peebles)
Which dark matter halos are “observable”?

Halos observable in neutral hydrogen

Abundance

dN/d log v [h^3 Mpc^{-3}]

v_{max} [kms^{-1}]

Halo mass

Simulated

Observed

Eagle

Sawala +13
2: “Cold dark matter predicts too many satellites”
CDM halo

Milky Way’s satellites

WDM halo

Credit: J.T.A. de Jong
Dark matter view (halos)  Observable view (galaxies)
3 “Massive substructures are too big not to host satellite”

Too big to fail? The puzzling darkness of massive Milky Way subhaloes

Michael Boylan-Kolchin, *↑ James S. Bullock and Manoj Kaplinghat

Measure halo mass of observed satellites

\[ V^2 = \frac{GM}{R} \]
No TBTF problem: halos lose mass
4: “Cold dark matter halos are cusped, observed haloes have cores.”

\[ V^2 = \frac{GM}{R} \]

\[ V_c \propto R \rightarrow \rho(R) = \text{const} \]

Oh +, 08
Does WDM generate cores?

The phase-space density of fermionic dark matter haloes

Shi Shao, Liang Gao, Tom Theuns and Carlos S. Frenk

Yes! But they are too small
The unexpected diversity of dwarf galaxy rotation curves

Kyle A. Oman\textsuperscript{1,*}, Julio F. Navarro\textsuperscript{1,2}, Azadeh Fattahi\textsuperscript{1}, Carlos S. Frenk\textsuperscript{3}, Till Sawala\textsuperscript{3}, Simon D. M. White\textsuperscript{4}, Richard Bower\textsuperscript{3}, Robert A. Crain\textsuperscript{5}, Michelle Furlong\textsuperscript{3}, Matthieu Schaller\textsuperscript{3}, Joop Schaye\textsuperscript{6}, Tom Theuns\textsuperscript{3}

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Eagle
Eagle

Tom Theuns
Understanding the shape and diversity of dwarf galaxy rotation curves in $\Lambda$CDM

J. I. Read$^1$, G. Iorio$^{2,3}$, O. Agertz$^1$, F. Fraternali$^{2,4}$

![Image of Starburst with $i_{true} = 15^\circ$](image)

![Graphs of rotation curves for different inclinations](graphs)

1 Theuns
Feedback can generate cores

Pontzen & Governato 13

Governato+12
Self-interacting dark matter scattering rates through cosmic time

Andrew Robertson*, Richard Massey, Vincent Eke, Richard Bower
Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK

Spreading out and staying sharp - Creating diverse rotation curves via baryonic and self-interaction effects

Peter Creasey¹*, Omid Sameie¹, Laura V. Sales¹, Hai-Bo Yu¹†, Mark Vogelsberger²† and Jesús Zavala³

[Graph showing the density profile of dark matter as a function of radius, with different colors for different scattering rates.]
No (?) issues with CDM when including galaxy formation physics
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Probing dark matter with quasars

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT
By Dr. M. SCHMIDT
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena
Nature, '63

z=7.1 ULAS J1120+064
Mortlock +, Nature 11

QS0 1422+231, 18 hours with KeckI
Lyα forest
QS0 Lyα emission

Counts
λ(Å)

Counts
λ(Å)
Intervening absorption in quasar spectra
A (very simple) intrinsic quasar spectrum

Flux

Ly-\(\alpha\) emission

1215.67(1 + z_{\text{qso}})\text{Å} \text{observed}

observed wavelength

Hydrogen atom

Hydrogen Energy Level Diagram

\(n = 1\)
Lyman Series
Ground State
\(E_n = -13.6 \text{ eV}\)

\(n = 2\)
Balmer Series
\(E_2 = -3.4 \text{ eV}\)

\(n = 3\)

\(n = 5\)
Free Electrons
\(E_n = 0 \text{ eV}\)

1215.67Å
Expected observed spectrum due to intervening absorption

\[ \tau \approx 13000h^{-1} \Omega_{\theta} \Omega_{m}^{2} (1 + z)^{3/2} \]

transmission = \exp(-\tau)

1215.67(1 + z_{\text{qso}})\text{Å} observed

Ly-\(\alpha\) emission

complete transmission

complete absorption

observed wavelength

1215.67Å

Hydrogen Energy Level Diagram

Free Electrons

Ground State

Lyman Series

Balmer Series

\(E_{n} = 0 \times 10^{-3}\)
Conclusion: the Universe is highly ionised

\[ \Gamma n_{\text{HI}} = \alpha n_{\text{HII}} n_e \]

Ionization rate from galaxies & quasars as computed by Haardt & Madau
Intervening absorption

Fan+03

Fan+01, 06
*Much* more absorption at higher redshifts

A lot of absorption

Complete transmission

Nearby quasar

Distant quasar
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Photo-ionisation also heats gas: photo-heating

Resulting temperature-density relation

Temperature / K

Density / mean density

Garzilli+15
Line broadening: thermal broadening

\[ N(v_z) = \frac{1}{\sqrt{2\pi kT/m}} \exp\left(-\frac{v_z^2}{2kT/m}\right). \]
Line broadening: Jeans filtering

(a) -- L3
- L1
- L0.3

(b)

(c)

(d)

(e)

ρ

v_p (km s⁻¹)

v_H (km s⁻¹)

e⁻τ
Line broadening = smoothing operation introduces a cut-off in the power spectrum

\[ b^2 = b_T^2 + b_p^2 \]

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Jeans filtering

thermal broadening

line width

line strength
Is the observed cut-off due to WDM? Or due to the temperature of the gas?
Mock quasar spectrum

Viel+13
Flux power spectra at different redshifts

\[ \Delta^2(k) \]

- **z=4.2**
- **z=4.6**
- **z=5**
- **z=5.4**

**Observed**

- **HIRES**
- **MIKE**
- **REF (best guess)**

**Mock**
(Lack of) degeneracy between thermal and WDM cut-off

\[ T_0^A (z=4.5) \text{ K} \]

\[ 1 \text{ KeV/m}_{\text{WDM}} \]
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Future:

- gravitational lensing - astro-ph 1512.06507
- satellites (again)
- stellar streams
- Relhics

Lensing: Vegetti +12

Eagle

Relhics

Benitez-Llambay +17
I want to be involved!

Welcome to the EAGLE Project

What is the EAGLE project?

EAGLE (Evolution and Assembly of GaLaxies and their Environments) is a simulation aimed at understanding how galaxies form and evolve. This computer calculation models the formation of structures in a cosmological volume, 100 Megaparsecs on a side (over 300 million light-years). This is large enough to contain 10,000 galaxies of the size of the Milky Way or bigger, enabling a comparison with the whole zoo of galaxies visible in the Hubble Deep field for example. This website contains downloadable images and movies, many of which are located in Highlights or Downloads.

The simulation starts when the Universe is still very uniform - no stars nor galaxies had formed yet - with cosmological parameters motivated by observations by the Planck satellite of the cosmic microwave background. Crucial parameters are the density of dark matter - which allows structures to grow, baryonic matter - the gas from which stars form, and the cosmological constant - responsible for cosmic acceleration.

Dark matter enables structures like galaxies to form, even while the Universe is expanding.
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