Towards an **Effective** **T**heory **O**f **S**tructure formation (ETHOS)

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TeV Particle Astrophysics, CERN, September 2016
The particle nature of dark matter is one of the biggest enigmas of particle astrophysics.

Dark Matter

DM particle physics

DM astrophysics

DM production

DM scattering rate

DM annihilation/decay rate

experiments on Earth

Particle Colliders

Direct Detection

experiments on space

Indirect Detection

The particle nature of dark matter is one of the biggest enigmas of particle astrophysics.
The particle nature of dark matter is one of the biggest enigmas of particle astrophysics.
most of these efforts rely on our knowledge of the DM phase space distribution across time

structure formation theory
The goal of structure formation is to explain the growth of cosmic structures across time (DM is seemingly essential).

Early Universe (t ~ 0.4 Myrs)

\[ \frac{\delta \rho_m}{\rho_m} \sim 10^{-3} \]

Universe today (t ~ 13.8 Gyrs)

\[ \frac{\delta \rho_m}{\rho_m} \gtrsim 1 \]

2MRS galaxy "map", large-scale structure

Andromeda

galactic scales

Credit: ESA and the Planck Collaboration

Huchra +12
The Cold Dark Matter (CDM) hypothesis is the cornerstone of the current structure formation theory. CDM assumes that the only DM interaction that matters is gravity!!

Cosmological simulations:
- DM gravity only
- "baryonic" physics (radiative cooling, gas hydrodynamics, star formation, supernova and AGN feedback, ...)

Credit: Illustris project

2000 CPU years!!
despite the spectacular progress in developing a structure formation theory, it remains incomplete since we still don't know:

what is the nature of dark matter?

What is the mass(es) of the DM particle(s) and through which forces does it interact?

In the physics of galaxies, is gravity the only dark matter interaction that matters?

Although there is no indisputable evidence that the CDM hypothesis is wrong, there are reasonable physical motivations to consider alternatives.
non-gravitational DM interactions and structure formation
What is the nature of dark matter?

Does DM interact with visible particles?

Scattering with nuclei

DM ↔ DM

SM ↔ SM

DM self-annihilation

DM ↔ SM

Interactions with visible particles are too weak to impact galaxy formation/evolution.

<table>
<thead>
<tr>
<th>Cross section $\sigma/m_\chi$ [cm²/gr]</th>
<th>Characteristic velocity $\bar{v}$ [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI $\chi$–nucleon $\lesssim 10^{-23}$</td>
<td>$\sim 200$</td>
</tr>
<tr>
<td>$m_\chi \in (0.1 - 5)$ TeV</td>
<td>(local halo)</td>
</tr>
<tr>
<td>LUX</td>
<td></td>
</tr>
<tr>
<td>$\chi\chi \rightarrow b\bar{b} \lesssim 10^{-10}$</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>$m_\chi \in (0.1 - 1)$ TeV</td>
<td>(dSphs)</td>
</tr>
<tr>
<td>Fermi-LAT</td>
<td></td>
</tr>
</tbody>
</table>

1 cm²/g $\sim$ 2 barns/GeV

Dark matter is quite “dark” (invisible)

Nucleon-nucleon elastic scattering:

$\sim 10$ cm²/gr
What is the nature of dark matter?

Can DM particles collide with themselves?

Constraint on DM self-collisions:

\[ \sigma / m \lesssim 2 \text{ cm}^2 / \text{gr} \]

Robertson+2016

Nucleon-nucleon elastic scattering:

\[ \sim 10 \text{ cm}^2 / \text{gr} \]

Stars (collisionless) follow the DM distribution.
What is the nature of dark matter?

Can DM particles collide with themselves?

[Diagram showing dark matter (DM) and cross section/mass vs. velocity dispersion graph with astro constraints (e.g., Bullet cluster).]
What is the nature of dark matter?

Can DM particles collide with themselves?

average scattering rate per particle:

\[ \frac{R_{sc}}{\Delta t} = \left( \frac{\sigma_{sc}}{m_\chi} \right) \bar{\rho}_{dm} \bar{v}_{typ} \]

\(~ 1 \text{ scatter / particle / Hubble time}\)

Neither a fluid nor a collisionless system:

\(~ \text{rarefied gas} \quad (\text{Knudsen number} = \lambda_{\text{mean}}/L > \sim 1)\)

constraints allow collisional DM that is astrophysically significant in the center of galaxies:

reduced inner DM densities in dwarf galaxies

astro constraints (e.g. Bullet cluster)
What is the nature of dark matter?

Can DM particles collide with themselves?

Constraints allow collisional DM that is astrophysically significant in the center of galaxies:

Velocity-dependent models (motivated by a new force in the “dark sector”) can accommodate the constraints e.g. Yukawa-like, Feng+09, Loeb & Weiner 2011,...

Graph showing cross section vs velocity dispersion for dwarf, MW, and cluster masses with constraints on DM-DM scattering.

- Reduced inner DM densities in dwarf galaxies
- Yukawa-like DM-DM scattering
- Astro constraints (e.g. Bullet cluster)
- Hard sphere DM-DM scattering
What is the nature of dark matter?

Can DM particles interact with other “dark” particles?

Allowed interactions between DM and relativistic particles (e.g. “dark radiation”) in the early Universe introduce pressure effects that impact the growth of DM structures (phenomena analogous to that of the photon-baryon plasma).

Dark radiation pressure counteracts gravity creating “dark acoustic oscillations”

Diffusion (Silk) damping can effectively diffuse-out DM perturbations

Once kinetic decoupling (DM-DR) occurs, DM behaviour is like CDM

Credit: Wayne Hu (U. Of Chicago)
What is the nature of dark matter? (summary)

the search for visible byproducts of DM interactions continues

dark matter is quite dark (invisible)

from a purely phenomenological perspective, it is possible that non-gravitational DM interactions play a key role in the physics of galaxies

dark matter might not be as “inert” as is commonly assumed
Beyond CDM: exploring new dark matter physics with astrophysics

From a purely phenomenological perspective, it is possible that non-gravitational DM interactions play a key role in the physics of galaxies.

Unsolved question: is the minimum mass scale for galaxy formation set by the DM nature or by gas physics (or by both)?

Unsolved question: are non-gravitational DM interactions irrelevant for galaxy evolution?

These questions go beyond the “standard” DM model for the formation and evolution of galaxies.

Pursuing them, will either confirm the standard model or unveil a fundamental DM property.
The nature of dark matter and the first galaxies

**Unsolved question:**
is the minimum mass scale for galaxy formation set by the DM nature or by gas physics (or by both)?

**Observations have yet to measure the clustering of dark matter at the scale of the smallest galaxies**

**Figure:**
- **Cosmic Cluster Galactic**
- **Linear power spectrum**
- **Non-linear (simulation)**
- **Linear (analytic)**
- **Baryon Acoustic Oscillations**
- **Unknown small scale behavior**
- **CDM**
- **DM is relativistic at earlier times thermal cut-off (free-streaming)**
- **DM interacts with relativistic particles at earlier times: DM-DR DAOs and Silk (collisional) damping**
- **Dwarf galaxies**

- **Kuhlen+12**
The nature of dark matter (evolution of structures)

Unsolved question:
are non-gravitational DM interactions irrelevant for galaxy evolution?

If gravity is the only relevant DM interaction, the central density of haloes is ever increasing

With strong self-interactions ($\sigma/m \gtrsim 0.5 \text{ cm}^2/\text{gr}$)
DM haloes develop “isothermal” cores

(Carlson+92, Spergel & Steinhardt 00, Yoshida+00, Davé+01, Colín+02, Rocha+13, Peter+13....)
The nature of dark matter (evolution of structures)

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Clues of new DM physics from dwarf galaxies?

Dwarf galaxies: most DM-dominated systems: $M_{DM} > 10 M_{VIS}$
(ordinary matter is less dynamically relevant)

Milky Way satellite (Fornax)

$M_{VIS} \sim 10^7 M_{Sun}$

The stellar dynamics is simplified and the underlying DM distribution can be more easily constrained

“Optimal” dynamical DM detectors
Clues of new DM physics from dwarf galaxies?

The properties of the smallest galaxies observed today are a challenge if gravity is the only DM interaction that matters.

Isolated dwarf (DDO 154)
$M_{\text{VIS}} \sim 10^8 M_{\odot}$

Milky Way satellite (Fornax)
$M_{\text{VIS}} \sim 10^7 M_{\odot}$

Abundance problem (Zavala+09, Klypin+15)

Structural problem (Boylan-Kolchin+11, Papastergis+14)

**Abundance problem**
- (Zavala+09, Klypin+15)

**Structural problem**
- (Boylan-Kolchin+11, Papastergis+14)

**CDM abundance problem**
- Observed galaxies (ALFALFA)
- CDM modeled galaxies (Zavala et al. 2009)

**CDM structural problem**
- Milky Way satellites

Simulated DM haloes
Clues of new DM physics from dwarf galaxies?

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**Structural problem** (Boylan-Kolchin+11, Papastergis+14)

Is dwarf galaxies

**CDM abundance problem**

**Simulated DM haloes**

**signature of a primordial damping in the DM power spectrum??**

**signature of DM self-interactions??**

**CDM structural problem**

- Observed galaxies (ALFALFA)
- ~ enclosed DM mass
- ~ rotational velocity [km/s]
- 0.4 radius [kpc] 1.0
Clues on new DM physics at other scales?

Cluster Abell 3827 (Massey +15)

claimed detection of ~1.6 kpc offset between the stars and DM centroids of elliptical galaxy N1

stars are (mostly) collisionless

\[ \sigma/m \sim 1.5 \text{ cm}^2/\text{gr} \]
(Kahlhoefer+15)

nucleon-nucleon elastic scattering:
\[ \sim 10 \text{ cm}^2/\text{gr} \]

reconstruction of the gravitational field in the MW using phase-space data from stellar tidal streams

Bovy et al. 2016

CDM + baryons \( \lesssim 0.8 \)

sphericity (c/a)
\[ r \sim 15 \text{ kpc} \]
\[ 1.05 \pm 0.14 \]

Cluster scales

Milky-Way scale
CDM + current galaxy modelling are successful in reproducing several properties of the galaxy population but:

**uncertain gas and stellar physics**

**outstanding challenges at the scale of the smallest (dwarf) galaxies**

the current situation offers an opportunity to approach the dark matter problem from a broader perspective...
Towards an **Effective Theory Of Structure formation (ETHOS)**

- **Early Universe**
  - DM production mechanism (verify consistency with global DM abundance)

- **structure formation**
- **invisible dark matter**
  - hidden DM physics
    - DM – dark photons
    - DM – DM collisions
    - Warm DM
    - Cold DM (gravity only)

- **visible matter**
  - gravity
    - gas and stellar physics

- **galaxy formation and evolution**

Generalize the theory of structure formation (CDM) to include a **broader range of allowed DM phenomenology** coupled with our knowledge of galaxy formation/evolution.

Signatures of non-gravitational DM interactions (dynamical, visible byproducts)
Developing ETHOS

DM interactions with relativistic particles in the early Universe

+ 

DM-DM self-scattering in the late Universe

In collaboration with:

Torsten Bringmann (UiO, Oslo)
Francis-Yan Cyr-Racine (Harvard, Cambridge)
Christoph Pfrommer (HITS, Heidelberg)
Kris Sigurdson (UBC, Vancouver)
Mark Vogelsberger (MIT, Cambridge)

ETHOS I:
Cyr-Racine, Sigurdson, Zavala +16
(arXiv:1512.05349)

ETHOS II:
Vogelsberger, Zavala +16
(arXiv:1512.05344)
ETHOS: classify DM models according to their effective parameters for structure formation

Particle physics parameters (masses, couplings, ...)

\[ \{ m_\chi, \{ g_i \}, \{ h_i \}, \xi \} \]

Select a particle physics model, e.g. DM interacting with massless neutrino-like fermion via massive mediator (e.g. van der Aarssen, Bringmann+12)

Growth of structures (linear regime) with additional physics: DM-DR-induced DAOs and Silk damping
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effective parameters

\[ \Xi_{\text{ETHOS}} = \left\{ \omega_{\text{DR}}, \{ a_n, \alpha_l \}, \left( \frac{\langle \sigma T \rangle_{v_{Mi}}}{m_\chi} \right) \right\} \]

\[ \omega_{\text{DR}} \equiv \Omega_{\text{DR}} h^2 \]

related to DR opacity to DM scattering (relative to early-time evolution)

DM self-scattering (relevant for late-time evolution)
ETHOS: classify DM models according to their effective parameters for structure formation

Particle physics parameters (masses, couplings, ...)

\[ \{ m_\chi, \{ g_i \}, \{ h_i \}, \xi \} \]

growth of structures (linear regime) with additional physics: DM-DR-induced DAOs and Silk damping

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\[ \Xi_{\text{ETHOS}} = \left\{ \omega_{\text{DR}}, \{ a_n, \alpha_l \}, \left\{ \frac{\langle \sigma_T \rangle v_{Mi}}{m_\chi} \right\} \right\} \]

All DM particle physics models that map into the same ETHOS parameters can be studied (constrained) at the same time

Example cases in ETHOS

Transfer cross section

Linear power spectrum

Graphs show linear power spectrum and transfer cross section for different DM models.
ETHOS application: non-linear regime with N-body simulations and the CDM challenges

Both CDM abundance and structural “problems” can be alleviated simultaneously.

Data: MW satellites

- CDM
- ETHOS-4

DM-dark radiation interactions suppress/delay the formation of small haloes (galaxies)

DM self-interactions reduce the central DM densities of haloes

ETHOS II: Vogelsberger+16
Developing ETHOS (self-scattering DM + baryonic physics)

“baryonic physics”: hydrodynamics, radiative cooling of gas, stellar population modelling, SNe feedback (AREPO code)

The signature of DM collisions could be imprinted in the stellar distribution of the smallest galaxies

simulation of a galaxy in Self-Interacting DM (Vogelsberger, Zavala +14)

\[ \sigma/m = 1 \text{ cm}^2/\text{gr} \]

\[ \sigma/m = 10 \text{ cm}^2/\text{gr} \]
Concluding remarks

An Effective (more generic) THeory Of Structure formation (ETHOS) must consider a broader range of allowed DM phenomenology coupled with our developing knowledge of galaxy formation/evolution

First highlights of the effective theory (ETHOS):

- Mapping between the particle physics parameters of a generic DM-DR interaction into effective parameters for structure formation ($P(k)$ and $\sigma_T/m$)

- All DM particle physics models that map into the same ETHOS parameters can be studied (constrained) at the same time

- The window for the DM particle nature to be relevant for structure formation is narrow and within reach of upcoming observations

\[
0.1 \text{ cm}^2/\text{gr} \lesssim \sigma/m \lesssim 2 \text{ cm}^2/\text{gr}
\]

\[
10^{9.5} M_{\text{Sun}} \lesssim M_{\text{cut}} \lesssim 10^{10.5} M_{\text{Sun}}
\]

- Dwarf galaxies might hide a clue of a fundamental guiding principle for a complete DM theory

Possible degeneracies in observational comparisons, albeit undesirable, reflect our current incomplete knowledge of the DM nature and galaxy formation/evolution
EXTRA SLIDES
ETHOS: classify DM models according to their effective parameters for structure formation

particle physics parameters (masses, couplings, ...)

\[ \{m_\chi, \{g_i\}, \{h_i\}, \xi\} \]

growth of structures (linear regime) with additional physics: DM-DR-induced DAOs and Silk damping

select a particle physics model e.g. DM interacting with masless neutrino-like fermion via massive mediator (e.g. van der Aarssen, Bringmann+12)

eqs. for DM perturbations

\[
\begin{align*}
\dot{\delta}_\chi + \theta_\chi - 3\phi &= 0, \\
\dot{\theta}_\chi - c_\chi^2 k^2 \delta_\chi + \mathcal{H} \theta_\chi - k^2 \psi &= i k_\chi [\theta_\chi - \theta_{\text{DR}}]
\end{align*}
\]

related to DR opacity to DM scattering (parameterize the collisional term of the Boltzmann eq.)

\[ C_{\chi\bar{\chi}\leftrightarrow\chi\bar{\chi}}[f_\chi, f_{\text{DR}}] \]
Or... the complexity of gas and stellar physics

Gas heating (UV background from first generation of stars/galaxies)

Gas and DM heating through supernovae

These mechanisms are certainly there, but how efficient they are remains unclear.

To some extent, they are degenerate with new DM physics.