The dark matter puzzle

Ultra-Light Axions (ULA)
Scalar-field, non-interacting

WIMPS
Schwabe & Niemeyer 2022

Françoise Combes
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Where is the dark matter?

Galaxy clusters

Planck : power spectrum $\Omega_b, \Omega_m, \Omega_\Lambda$

Abell 370
The WIMP miracle

Possible to obtain the required abundance of dark matter with particles of mass $\sim 100 \text{ GeV}$, with the weak interaction force annihilation rate $<\sigma v> \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$

In early Universe, abundance of particles is « frozen », they decouple when their interaction

$\mathbf{n} <\sigma v> \sim 1/t_{\text{hubble}}$

**Coincidence:** corresponds to the lightest particle of super-symmetry (neutralino)

**But in LHC:** no super-symmetry, No new particle!
### Particles beyond standard model?

<table>
<thead>
<tr>
<th>fermions (3 générations de la matière)</th>
<th>bosons (forces)</th>
</tr>
</thead>
<tbody>
<tr>
<td>quark mass: up (2,4 MeV/c²)</td>
<td>photon (0 MeV/c²)</td>
</tr>
<tr>
<td>charge: up (2/3)</td>
<td>charge: photon (0)</td>
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<tr>
<td>spin: up (1/2)</td>
<td>spin: photon (1)</td>
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<tr>
<td>name: up</td>
<td>name: photon</td>
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<tr>
<td>quark mass: charm (1,27 GeV/c²)</td>
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<td>charge: charm (2/3)</td>
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<td>spin: charm (1/2)</td>
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<td>name: charm</td>
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<tr>
<td>quark mass: bottom (171,2 GeV/c²)</td>
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<td>charge: bottom (2/3)</td>
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<td>spin: bottom (1/2)</td>
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**From the Big-Bang**
- ~400 photons/cm³
- ~300 neutrinos/cm³
- 0,1 billions of billions/s cross us

→ **Search for WIMPS since 1985**

**Extension to sterile neutrinos?**
Ly-α: constraints on m(warm)

25 quasars $z > 4$: spectra obtained at Keck \textit{(Viel et al 2013)}
Ly-α forest and comparison with simulations \( m_{\text{WDM}} > 3.3 \text{ keV} \) (2σ)

\[ \Lambda \text{CDM} \]
\[ \text{WDM 2 keV} \]
\[ \text{WDM 1 keV} \]

WDM, \( m_X > 4.65 \text{ keV} \) thermal relics
\( m_s > 29 \text{ keV} \) non-resonant production
Primordial Black holes

$\beta = \rho_{\text{PBH}}/\rho_{\text{tot}}$

$\gamma$, yellow: neutron capture, GW

For $M \sim 10^{15} g$, too many $\gamma$-rays produced

Since PBH form in the radiative era, they can be considered as non-baryonic, and $=\text{CDM}$

However, their mass is limited by MACHOS, EROS experiments

Small masses evaporate

Gutierrez et al 2017
Candidates for the dark matter

New physics, beyond the standard model SM

- Kaluza-Klein DM in UED
- Kaluza-Klein DM in RS (Randall-Sundrum)
  - Axion
  - Axino
  - Gravitino
  - Photino
  - SM Neutrino
  - Sterile Neutrino
    - Sneutrino
    - Light DM
    - Little Higgs DM
    - Wimpzillas
  - Cryptobaryonic DM
  - Q-balls

- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworld DM
  - Heavy neutrino
  - Neutralino (WIMP)
  - Messenger States in GMSB
  - Branons
  - Chaplygin Gas
  - Split SUSY
  - Primordial Black Holes
  - Mirror Matter

...
Fuzzy dark matter

Cusps exist in galaxy clusters, but not in galaxies.
In dwarf galaxies, cores of ~1 kpc

Bosons generated in non-thermal mechanisms $\rightarrow$ axions 
(\textit{ALP, Marsh 2016}) cold particles, which can collapse
BEC “Bose-Einstein condensate”, macroscopic state at low T

- Finite mass, very small, $\lambda$ de Broglie, $\lambda_{dB} = \frac{h}{m_{a}v}$
$\Rightarrow \lambda_{dB} = 1-2$ kpc

- In fact $\lambda_{dB} \sim 1-2$ kpc for $m_{a} = 10^{-22}$ eV, and $v \sim 10$ km/s

For masses $m_{a} = 10^{-22}$ eV, quantum pressure prevents the formation of structures below $M_{cut} = 3 \times 10^{8} m_{22}^{-3/2} M_{\odot}$ (\textit{Hui et al 2017})
A long history

Already 40 yrs!

Baldeschi, Gelmini, Ruffini (1983)
Galactic dark matter halos made of fermions of \( m = 10^{-3} \) eV,
or bosons of \( m = 10^{-24} \) eV

Mass-size relation for equilibrium
For \( M \sim 10^{12} M_\odot \), \( R \sim 30\text{kpc} \)

\( M/R = 9.9 \hbar^2 / G m^2 \)

\( \sin (1994) \) rotation curves with pseudo Nambu-Goldstone boson

\( H u \ et \ al \ (2000) \), are they self-interacting (SI) or not?
Scalar field SFDM \( \rightarrow \) SI-SFDM
Böhmer & Harko (2007)

\( H u i \ et \ al \ (2017) \) review and revisit the problem: \( m > 10^{-21} \) eV
Fluctuation spectrum

Temperature anisotropies are undistinguishable from $\Lambda$CDM
*Foidl & Rindler-Daller 2022*

Scalar-field DM (SFDM without self-interaction $\rightarrow$ FDM)
Or Ultra-light actions (from QCD) $\rightarrow$ cut the high spatial frequencies $k$

CMB acoustic modes
Simulations AMR: eq. Schrödinger- Poisson

Core= soliton, Halo= clumpy aspect + wavy (Schive +2014)
Quantum interferences: 9 orders of magnitude

Schive et al 2014
Milky Way: Aquarius, satellites

Nori et al 2023  AX-GADGET, compared with CDM

Expected scaling law $\rho_c \sim R_c^{-4}$ while observations say $\rho_c \sim R_c^{-1}$

$\Sigma = 150 M_\odot/\text{pc}^2$

Donato et al 2009

Zoom x 5
Milky Way: Aquarius, satellites

Nori et al 2023

Comparison with CDM and also when $\text{Msat} > \text{Mcut}$ only (CDM-CUT)
Evolution with redshift

Nori et al 2023

$z=4$ to $z=0$,

From light to dark lines

Even if density curves flatten
the asymptotic equilibrium
is not reached at $z=0$
Due to the mass cut-off, halos are linked with thin filaments.
Filaments do not fragment!

May & Springel 2022

Search for structures have to increase threshold

Big problem of resolution, to resolve the de Broglie length
Simulations of a dwarf galaxy

Assuming gas and star formation, stochastic and stationary
Inducing fluctuations, different from white noise (n=0)

Ramses simulation of an isolated dwarf galaxy (Read et al 2016)
$M_{200} = 10^9 M_\odot$, $f_g=0.15$, concentration 22.23

Cusp is mitigated in a Hubble time (Hashim et al 2023)

Box = 5kpc Important fluctuations due to SF, SN
Core formation?

The slope of the radial density distribution is smoothed out, although not tending to a flat core.

$T_{\text{relax}} = 13.2 \text{ Gyr}$

*Hashim et al. 2023*
The case of Eridanus II

In this ultrafaint dwarf galaxy, there exists an old star cluster, which existence and size put also a constraint

Heating due to core oscillations $\Rightarrow m_a > 10^{-19}$ eV

May be the region inside the core is not completely valid

There are resonances for the oscillations

*Marsh & Niemeyer 2018*
**High-z massive galaxies?**

*Gong et al 2022*  

JWST found numerous galaxies $7 < z < 11$

Big problem if star formation is made in the whole mass function of galaxies

→ Too many UV to reionize the Universe  
Contradiction to Planck CMB

FDM, but also WDM with sterile neutrinos  
→ Suppress small-mass galaxies

![Graph showing mass function for different values of neutrino mass and redshift](image)
MOND = MOdified Newton Dynamics

At weak acceleration

\[ a \ll a_0 \] MOND regime \[ a = \left( a_0 a_N \right)^{1/2} \]

\[ a \gg a_0 \] Newtonian \[ a = a_N \]

\[ a_0 = 10^{-10} \text{ m/s}^2 \sim 10^{-11} \text{g} \]
Milgrom (1983)

Asymptotically

\[ a_N \sim 1/r^2 \implies a \sim 1/r \]
\[ \implies V^2 = \text{cste} \]

Covariant theory: TeVeS
\[ \implies \text{Gravitationnal lenses} \]
Bekenstein 2004

Conformal Gravity: Mannheim et al 2012

\[ \frac{M_{\text{dyn}}}{M_{\text{vis}}} = f\left( \frac{a_N}{a_0} \right) \]

\[ \frac{V_{\text{obs}}^2}{V_b^2} = a/a_N \]

\[ a_0 = 10^{-10} \text{ m/s}^2 \]
Success at weak surface densities

\[ \Sigma < \Sigma_0 \sim 150 \, M_\odot/pc^2, \quad \Rightarrow \text{the critical acceleration } a_0 \]

In particular dwarf galaxies

The rotation curves of all galaxy types

\[ a << a_0 \]

N1560

\[ a > a_0 \]

N2903

TF relation
Influence of the dark halo?

Dynamics of galaxies,
Formation of spirals and bars

TeVeS covariant theory \( \Rightarrow \) but unstable
ruled out by gravitational waves \( (c_{GW} \neq c) \)
But Skordis et al 2019, new version, with \( c_{GW} = c \)
New theory with Vector field

Unit time-like vector
Gravitational lensing
\( c_{GW} = c \)
Summary: axions or modified gravity?

Many constraints on the mass $m_a$, but not definitive

Some baryons+DM simulations (Aquarius, AX-Gadget, AxiREPO)

Approximations: cut-off of small structures (but negative pressure?) SP fluid, Madelung approx, SI or not? Repulsive quantum force?

Interactions SMBH and soliton? (same order of masses)

Lyman-α forest? $\Rightarrow m > 21 \ 10^{-22} \text{ eV}$ (Nori et al 2019)

Small halos (dwarfs) are less dense, larger cores
Massive halos, denser, unresolved solitons