Particle Physics & the Early Universe

Laura Covi

Institute for Theoretical Physics
Georg-August-University Göttingen
Outline

Lecture 1: Standard Cosmology & the cosmological parameters

Lecture 2: Thermal Universe and Big Bang Nucleosynthesis

Lecture 3: Inflation & the CMB

Lecture 4: Structure Formation & Dark Matter

Lecture 5: Baryogenesis
Lecture 4: Outline

- Dark Matter evidence & Structure Formation
- Neutrinos as Dark Matter
- (Some) Dark Matter Candidates and how to detect them
- Conclusions
Dark Matter and Structure Formation
DARK MATTER EVIDENCE

CLUSTER SCALES:

The early history of Dark Matter: In 1933 F. Zwicky found the first evidence for DM in the velocity dispersion of the galaxies in the COMA cluster... Already then he called it DARK MATTER!
DARK MATTER EVIDENCE

CLUSTER SCALES:

Nowadays even stronger result from X-ray emission: the temperature of the cluster gas is too high, requires a factor 5 more matter than the visible baryonic matter...
CLUSTER SCALES:

Systems like the Bullett cluster allow to restrict the self-interaction cross-section of Dark Matter to be smaller than the gas at the level

\[ \sigma \leq 1.7 \times 10^{-24} \text{cm}^2 \sim 10^9 \text{pb} \quad (m = 1 \text{ GeV}) \]

One order of magnitude stronger constraint by requiring a sufficiently large core...

Similar bounds from the sphericity of halos...

[Markevitch et al 03]

[Yoshida, Springer & White 00]
DARK MATTER EVIDENCE

GALACTIC SCALES:

the stars in the outer part of galaxies are faster than expected...

\[ \nu_c^2 \propto G N \frac{M(r)}{r} \propto \frac{M_{tot}}{r} \]

But instead it is constant! Need

\[ M(r) \propto r, \text{ i.e. } \rho_{DM} \propto r^{-2} \]
DARK MATTER EVIDENCE

GALACTIC SCALES:
Many density profiles, inspired by data or numerical simulations:
- Isothermal
- NFW
- Moore
- Kratsov
- Einasto, etc....
They mostly differ in the behaviour at the centre, either cusped or cored!

$$\rho(r) = \frac{\rho_0}{(r/R)^\gamma[1 + (r/R)^\alpha]^\frac{(\beta-\gamma)}{\alpha}}$$

Critical for indirect detection!
Dark Matter local density & velocity distribution

[Catena & Ullio 09, 11]

Critical for Direct Detection!
DARK MATTER EVIDENCE

HORIZON SCALES:

From the position and height of the CMB anisotropy acoustic oscillations peaks we can determine very precisely the curvature of the Universe and other background parameters.

<table>
<thead>
<tr>
<th>Particles</th>
<th>$\Omega h^2$</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baryons</td>
<td>0.0224</td>
<td>Cold</td>
</tr>
<tr>
<td>Neutrinos</td>
<td>&lt; 0.01</td>
<td>Hot</td>
</tr>
<tr>
<td>???</td>
<td>0.11-0.13</td>
<td>Cold</td>
</tr>
</tbody>
</table>

[Planck coll. 1502.01589]
Initial conditions

At recombination $z \sim 1100$ density/temperature fluctuations were at the order of $1/100000...$
How can they be the seed of structure today?
Following the fluctuations

We need seeds of small fluctuations, that were amplified by gravity & are the origin of the structure we see today
What happens after such perturbations "re-enter" the horizon?

In the Newtonian limit we have for the density perturbations of a matter fluid $\delta = \frac{\delta \rho}{\rho}$

$$\ddot{\delta}_k + 2H \dot{\delta}_k + \left( \frac{c_s^2 k^2}{a^2} - 4\pi G \rho \right) \delta_k = 0,$$

where $c_s = \frac{\delta p}{\delta \rho}$ is the sound speed in the plasma. Again a linear equation with a negative "mass" term... The fluctuations with negative mass grow and those have $k$ below $k_J$, i.e. a physical wavelength larger than the Jeans length:

$$\lambda_J = \frac{2\pi a}{k} = c_s \sqrt{\frac{\pi}{G \rho}} \simeq \frac{c_s}{H}$$

sound horizon

How strongly do they grow? The growing solution is

$$\delta_k \sim C_1 H \int \frac{dt}{a^2 H^2} + C_2 H \sim C_1 t^{2/3} + C_2 t^{-1}$$

for matter dominance

NOTE: much weaker than exponential due to the expansion friction term $\propto H$! Also if the expansion is dominated by radiation, the growth is inhibited and at most only logarithmic in time. We need a long time of matter dominance to make initial fluctuations become large...
Structure Formation

V. Springel @MPA Munich

$z=18.3 \ (0.21 \ \text{Gy})$

$z=5.7 \ (1 \ \text{Gy})$

$z=0 \ (13.6 \ \text{Gy})$

$z=1.4 \ (4.7 \ \text{Gy})$
FLUCTUATIONS ON ALL SCALES

Non-linear

Intergalactic hydrogen clumping

Gravitational lensing

Weak Lensing Tomography

Cluster abundance

Cosmic microwave background

Linear

[Tegmark]
Neutrinos as Hot Dark Matter
**Neutrino as (Prototype) DM**

Massive neutrino is one of the first candidates for DM discussed; for thermal SM neutrinos:

\[ \Omega_\nu h^2 \sim \frac{\sum_i m_\nu_i}{93 \text{ eV}} \]

but \( m_\nu \leq 2 \text{ eV} \) (Tritium \( \beta \) decay) so \( \Omega_\nu h^2 \leq 0.07 \).

Unfortunately the small mass also means that neutrinos are **HOT DM**... Their free-streaming is non negligible and the LSS data actually constrain \( m_\nu \leq 0.27 \sim 1 \text{ eV} \) \( \Rightarrow \Omega_\nu \ll \Omega_{DM} \).

**NEED** to go beyond the Standard Model!
Neutrino as (prototype) DM

Massive neutrino is one of the first candidates for DM discussed; for thermal SM neutrinos:

\[ \Omega_\nu h^2 \sim \frac{\sum_i m_{\nu_i}}{93 \text{ eV}} \]

but \( m_\nu \leq 2 \text{ eV} \) (Tritium \( \beta \) decay) so \( \Omega_\nu h^2 \leq 0.07 \)

Unfortunately the small mass also means that neutrinos are HOT DM... Their free-streaming is non negligible and the LSS data actually constrain \( m_\nu \leq 0.27 \sim 1 \text{ eV} \)

\[ \Omega_\nu \ll \Omega_{DM} \]

NEED to go beyond the Standard Model!
Neutrino as HDM

Even massive neutrinos remain relativistic for a long time and their free-streaming suppresses fluctuations on small scales

[Lesgourgues & Pastor '14]

\[ f_\nu \sim 0.01 \]

\[ f_\nu \sim 0.02 \]

\[ f_\nu \sim 0.1 \]
Neutrino as HDM

The suppression at small scales reduces the lensing potential at such scales and modifies the lensing signal in the CMB and the LSS & BAO as measured by galaxies surveys.

Degeneracy with $\sigma_8$
Effect from WDM

Also heavier/less relativistic particles can have an effect & their free-streaming suppresses fluctuations on smaller scales

[Maio & Viel ’15]
WDM & the Power spectrum

WARM DM suppresses perturbations on scales smaller than its free-streaming length:

\[ \lambda_{FS} \sim \text{Mpc} \left( \frac{m_{WDM}}{1\text{keV}} \right) \]

Compare with the data:

\[ m_{WDM} > 4 \text{ keV} \]

[Viel et al. ’07]
\[ M_{\text{cut}} \sim 10^9 M_\odot \left( \frac{N_\nu \alpha_\nu \alpha_\chi}{2 \times 10^{-4}} \right) \left( \frac{m_\chi}{1\text{TeV}} \right)^{-3/4} \left( \frac{m_\phi}{1\text{MeV}} \right)^{-3} \]
Neutrino as DR

[Lesgourgues @ Ferrara Meeting ’14]

Define two phenomenological parameters changing the perturbation equations:

1) Effective sound speed: \( \delta p = c_{\text{eff}}^2 \delta \rho \)

2) Effective viscosity speed \( c_{\text{vis}} \) controlling the amount of anisotropic pressure / shear

Archidiacono et al. 2011
inspired from Hu 1998,
Trotta & Melchiorri 2004...

other Dark Radiation candidates,
maybe interacting (EFFECTIVE)

scalar field oscillating in quartic potential (EXACT)
Neutrinos as DR

[Planck 1502.01589]
Dark Matter Production Mechanisms
Zeldovich-Lee-Weinberg bound

Two possibilities for obtaining the “right” value of $\Omega_\nu h^2$: decoupling as relativistic species or as non-relativistic! In-between the density is too large!

$m_\nu > 4(12)\text{GeV}$ for Dirac (Majorana)
THE WIMP MECHANISM

Primordial abundance of stable massive species

The number density of a stable particle $X$ in an expanding Universe is given by the Boltzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = \langle \sigma(X + X \rightarrow \text{anything})v \rangle (n_{eq}^2 - n_X^2)$$

Hubble expansion \hspace{1cm} Collision integral

The particles stay in thermal equilibrium until the interactions are fast enough, then they freeze-out at $x_f = m_X / T_f$

defined by $n_{eq} \langle \sigma_A v \rangle_{x_f} = H(x_f)$ and that gives

$$\Omega_X = m_X n_X(t_{now}) \propto \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties

For $m_X \approx 100$ GeV a WEAK cross-section is needed!

Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM!
Boltzmann equation

\[
\frac{dY}{dx} = -\frac{2\pi g_S}{15} \left( \frac{10}{g_\rho} \right)^{1/2} \frac{M_P}{m} \langle \sigma v \rangle_x (Y^2 - Y_{eq}^2)
\]

where $Y = n/s$, $x = m/T$, $g_\rho$ denote the number of degrees of freedom for entropy and energy density and we defined

\[
\langle \sigma v \rangle_x = \frac{1}{4x^4 K_2^2(x)} \int_{2x}^\infty dz z^2 \tilde{\sigma} \left( \frac{x}{z} \right) K_1(z)
\]

where we defined

\[
\tilde{\sigma} \left( \frac{m}{\sqrt{s}} \right) = (s - 4m^2)\sigma(m, s) = s\beta^2 \sigma(\beta)
\]

and $K_i(x)$ are modified Bessel functions coming from Maxwell-Boltzmann statistics

[Gondolo & Gelmini 91]
**SuperWIMP/FIMP paradigms**

Add to the BE a small decaying rate for the WIMP into a much more weakly interacting (i.e. decaying !) DM particle:

\[ \sum \sigma = 100 \text{ TeV} \]
\[ \sum \sigma = 10 \text{ TeV} \]
\[ \sum \sigma = 1 \text{ TeV} \]
\[ \sum \sigma = 500 \text{ GeV} \]

**[G. Arcadi & LC 13]**

**[Hall et al 10]**

**FIMP**

DM produced by WIMP decay in equilibrium

**[Feng et al 04]**

**SuperWIMP**

DM produced by WIMP decay after freeze-out

Two mechanism naturally giving “right” DM density depending on WIMP/DM mass & DM couplings
Strong CP & the Axion

The QCD vacuum has a non trivial structure, as a superposition of different topological configurations, giving rise to strong CP problem from the term:

$$\mathcal{L} = \theta \frac{\alpha_s}{8\pi} F^b_{\mu\nu} \tilde{F}^\mu\nu$$

[\text{\textsuperscript{t} Hooft 76}]

But from the bounds on neutron el. dipole moment $\theta < 10^{-9}$

Peccei-Quinn solution: add a chiral global U(1) and break it spontaneously at $f_a$, leaving the axion, a pseudo-Goldstone boson, interacting as

$$\mathcal{L}_{PQ} = \frac{\alpha_s}{8\pi f_a} a F^b_{\mu\nu} \tilde{F}^\mu\nu$$
Axions as Dark Matter

The axion is also a very natural DM candidate, but in this case in the form of a condensate, e.g. generated by the misalignment mechanism:

Before the QCD phase transition the potential for the axion is flat

After the QCD phase transition a potential is generated

\[ V(a) = \Lambda_{QCD}^4 \left( 1 - \cos \left( \theta + \frac{a}{f_a} \right) \right) \]

by instantons effects and the axion starts to oscillate coherently around the minimum:

zero momentum particles $\gg$ CDM!
Axions as Dark Matter

Their energy density by misalignment is

$$\Omega_a h^2 = 0.5 \left( \frac{f_a}{10^{12}\text{GeV}} \right)^{7/6} \theta_i^2$$

Axions can contribute to star/SN cooling and so

$$0.5 \times 10^{10}\text{GeV} \leq f_a \leq 10^{12}\text{GeV}$$

Therefore the mass for axion DM is very small:

$$m_a = \frac{\Lambda^2_{QCD}}{f_a} \sim 6 \times 10^{-5}\text{eV} \left( \frac{f_a}{10^{11}\text{GeV}} \right)^{-1}$$

[Raffelt 98]
The right abundance can be obtained if the Peccei-Quinn scale is of the order of $10^{11-12}$ GeV and the mass in the $\mu$ eV.

ADMX is finally touching the expected region.

But it could be much wider for non-standard cosmologies...

[Carosi '07]

[Gondolo et al 09]
AXION DM SEARCHES

AXION Coupling $|g_{\gamma\gamma}|$ (GeV$^{-1}$)

- ADMX Published Limits
- ADMX Upgrade in Progress Target Sensitivity
- ADMX HF R&D
- Non-RF-cavity Techniques
- White Dwarf and Supernova Bounds

Axion Mass ($\mu$eV)

- Too Much Dark Matter
- Axion Cold Dark Matter
- Minimum Coupling
- ADMX Next Generation Target
- "Hadronic" Coupling

Cavity Frequency (GHz)

http://www.phys.washington.edu/groups/admx/home.html
We have strong evidence for DM from gravity, but the nature of Dark Matter is still unclear… It requires to go **Beyond the Standard Model**, probably most “natural” candidates are WIMPs, SuperWIMPs, axions!

The WIMP mechanism is being probed already by astrophysical observations and particle physics experiments. Some hints were found, but no confirmation so far…

Keep looking and doing model-building!
References

Review on neutrinos in cosmology:
Julien Lesgourgues & Sergio Pastor,
“Neutrino cosmology and Planck”,

Reviews on Dark Matter, especially Indirect Detection:
- G. Bertone, D. Hooper, J. Silk
- A. Ibarra, D. Tran, C. Weniger