2. Dark matter properties from cosmology & astrophysics

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DM EVIDENCE @ MANY SCALES

CMB anis. (Growth & Pattern of) Large Scale Structures
Clusters (X-rays, lensing)
Galaxies (rotation curves, fits...)
Dwarfs

“Cosmological”

(growing effect of non-linearities, baryonic gas dynamics, feedbacks...)

“Astrophysical”

Especially cosmological evidence of paramount importance for Particle Physics!

› Exact solutions or linear perturbation theory applied to simple physical systems: credible and robust!
› Many would say: Suggests “cold” collisionless additional species, rather than a modification of GR (IMHO: academic debate mostly influenced by “classical” thinking… the need for new d.o.f. is key observation!)
› Tells that its majority is non-baryonic, rather than e.g. brown dwarf stars, planets...

Beyond SM explanation needed, but gravity is universal: no particle identification!
Discovery via other channels is needed to clarify particle physics framework
But what to look for depends on “theoretical prejudice” (curse of DM searches)
TWO COMMENTS

- Don’t be (too) fooled by the whole debate dark matter vs. modified gravity

- Do we really need new degrees of freedom?
  Among fundamental particles of the SM, only neutrinos are at most weakly charged (i.e. “dark”, or invisible if you prefer) massive and cosmologically stable, we’ll see if they work.
“DM OR MODIFIED GRAVITY”?

The difference between the two may be less sharply defined than you naively think!

Ex.: take one of the most frequently considered models of modified gravity, $f(R)$


$$S_{\text{met}} = \frac{1}{2\kappa} \int d^4x \sqrt{-g} f(R) + S_{\text{M}}(g_{\mu\nu}, \psi).$$

equivalent to

$$S_{\text{met}} = \frac{1}{2\kappa} \int d^4x \sqrt{-g} [\phi R - V(\phi)] + S_{\text{M}}(g_{\mu\nu}, \psi)$$

where $\phi = f'(R)$ $V(\phi) = R(\phi)\phi - f(R(\phi))$

In particular, the simplest such theory adds a quadratic term in Ricci scalar ($R^2 \ldots$)

$$S_G = \int \sqrt{g} \left\{ -\Lambda^4 - \frac{M_{\text{Pl}}^2}{2} R + \frac{M_{\text{Pl}}^2}{12 m_0^2} R^2 + \ldots \right\}$$

Equivalent to a theory with a scalar of mass $O(m_0)$

In the low curvature scenario $R << m_0^2$ this is **standard GR + massive scalar** minimally coupled to matter, with $\phi$ linearly coupled to the trace of the energy momentum tensor

$$\mathcal{L}_{\phi-T_{\mu\nu}} = \frac{1}{M_{\text{Pl}}\sqrt{6}} \phi T_{\mu}^{\mu}$$

“DM OR MODIFIED GRAVITY”? 

It is possible for \( \phi \) to be the DM (a “light one”, \( \sim \text{meV} \) to \( \text{MeV} \)) produced via the misalignment mechanism (see last lecture), and decaying into \( \gamma \gamma \) via a Planck-mass & loop suppressed coupling

\[
\mathcal{L}_{\phi-SM}^{\text{tree-level}} = \frac{1}{M_{\text{Pl}} \sqrt{6}} \phi \left\{ 2 m^2_{\Phi} \Phi^2 - \nabla_\mu \Phi \nabla^\mu \Phi \right\} + \sum_{\psi} m_\psi \bar{\psi} \psi - 2 m^2_W W^+_\mu W^-_\mu - m^2_Z Z_\mu Z^\mu \]

\[
\mathcal{L}_{\phi-SM}^{\text{one-loop}} = \frac{1}{M_{\text{Pl}} \sqrt{6}} \phi \left\{ \frac{\alpha_{\text{EM}} c_{\text{EM}}}{8\pi} F_{\mu\nu} F^{\mu\nu} + \frac{\alpha_s c_G}{8\pi} G^a_{\mu\nu} G^{a\mu\nu} \right\},
\]

\[
\Gamma_{\phi \rightarrow \gamma \gamma} = \frac{\alpha^2_{\text{EM}} m_0^3}{1536\pi^3 M^2_{\text{Pl}}} |c_{\text{EM}}|^2
\]

\[
\Gamma_{\phi \rightarrow \gamma \gamma} \simeq \left[ 2.5 \times 10^{29} \text{s} \left[ \frac{1\text{MeV}}{m_0} \right]^3 \right]^{-1}
\]

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**How would you call that? A DM candidate? A modified gravity scenario? Note that the best you could hope to find is that DM decay is somewhat related to the Planck scale...**
SO, MUCH ADO ABOUT NOTHING?

Well, not really:

you may still ask yourself if there are modifications to the known **long-range force** (IR phenomenon!) directly coupled to the energy momentum tensor (≈ "responding to mass")

You may think of it as a **quantitative rather than qualitative** difference wrt DM:

- e.g. is the **mass scale** associated to the **new degrees of freedoms** ≪10⁻²⁰ eV scale we have directly probed in the Solar System (maybe of the level of 10⁻³³ eV associated to the Hubble scale) **or way above it**?

- another way to look at it: is the dynamics we see the manifestation of the **exchange of light virtual particles** “universally coupled to all matter” *(note: even in this case we expect that these particles can be produced!)* **or** to the standard universal gravitational coupling of **real** (relatively heavier) **new particles** to the matter we see?

All the evidence from O(10 Gpc) down to at least O(Mpc)-linear or quasi-linear regime-consistent with the latter hypothesis & no solid alternative of the first type has emerged, while at small scales it is not conclusive, and in the solar system one certainly needs neither

**For its minimality, henceforth we stick to the latter hypothesis (DM), i.e. new physics responsible for DM only in the UV rather than also in the IR**
**NEUTRINOS AS DARK MATTER?**

**Condition 1. Must be massive** (which is already a departure from SM...)

**Fulfilled!** Oscillations established, at least 2 massive states, measured splitting implies at least one state heavier than 0.05 eV

\[
\Delta m_{\text{atm}}^2 \approx 2.4 \times 10^{-3} \text{ eV}^2
\]

**Condition 2. Must match cosmological abundance**

**Failed!** Direct mass limits combined with splittings from oscillation experiments impose upper limit of about 7 eV to the sum (After KATRIN, potentially improved to \(~0.7\) eV)

\[
\Omega_{\nu} = \frac{\rho_{\nu}}{\rho_c} \approx \frac{\sum_i m_i}{45 \text{ eV}}
\]

\[
\Omega_{\text{DM}} \approx 0.3(\text{Planck}) \Rightarrow \sum m_i \approx 15 \text{ eV}
\]

*we will perform this computation in lecture 3*

**Condition 3. Must allow for structure formation (of the right kind)**

**Failed!** This is a powerful argument excluding general classes of candidates (relativistic relics as DM, or so-called hot DM)
**DM IS NOT “HOT” (IT IS NOT RELATIVISTIC)!**

*dark matter is not “hot”: cannot have a relativistic velocity distribution (at least from matter-radiation equality for perturbation to grow)*

This is the more profound reason why neutrinos would not work as DM, even if they had the correct mass: they were born with relativistic velocity distribution which prevents structures below $O(100 \text{ Mpc})$ to grow till late!

**Cartoon Picture:**

ν’s “do not settle” in potential wells that they can overcome by their typical velocity: compared with CDM, they suppress power at small-scales

**More quantitative picture:**

see R. Sheth on perturbation growth in radiation era (but some more notions in Lec. 4)
THE NUMERICAL PROOF

ΛCDM run vs. cosmology including neutrinos (total mass of 6.9 eV)

simulation by Troels Haugbølle, see

http://users-phys.au.dk/haugboel/projects.shtml
Phenomenologically, we only ask that DM interaction rate $\Gamma = \sigma n v$ is “small. But we only measure DM energy density $\rho$, not $n$. Hence $\Gamma = (\sigma/m) \rho v$ small only requires $(\sigma/m)$ small!

Composite/macroscopic object may make the DM, if $\sigma/m$ small enough. Also, must be done before BBN. 2 possibilities in the SM I am aware of

**QCD strangelets** (E. Witten, PRD 30, 272 (1984), See also J. Madsen, astro-ph/9809032), require
- that the most stable form of hadronic matter is one containing strange quarks (u-d-s “nuggets”), if the opening of a third “Fermi well” is not (over)compensated by the larger mass penalty for s quark
  *answer to this conjecture still unknown*
- a first order QCD phase transition
  *Lattice studies show that this is not realized Y. Aoki et al. Nature 443, 675 (2006) [hep-lat/0611014]*
  *Even if strangelets could exist, no mechanism present in the SM to make them the DM (might still make DM if BSM degrees of freedom alter early universe…)*

**Primordial Black Holes (PBHs)**
*Highly constrained & require new physics, anyway (more in a moment)*
PRIMORDIAL BLACK HOLES (PBH)

Need a mechanism seeding the small scale primordial perturbation allowing for direct collapse to BHs before BBN. This only “shifts” the need for new physics to the dynamics of this mechanism, usually non-minimal inflationary scenarios, e.g. S. Clesse and J. García-Bellido, “Massive Primordial Black Holes from Hybrid Inflation as Dark Matter and the seeds of Galaxies," PRD 92, 023524 (2015) [1501.07565]

features responsible for direct collapse to BH @ horizon crossing

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T. Bringmann, P. Scott , Y. Akrami, PRD 85, 125027 (2012) [1110.2484]
Even so, a number of constraints exist which exclude a dominant “monochromatic” PBH contribution to DM at any mass but $10^{-14}$-$10^{-9} \, M_\odot$ (potentially excluded as well) see e.g. F. Capela, M. Pshirkov, P. Tinyakov, PRD 90, 083507 (2014) [arXiv:1403.7098] & refs. therein

BH evaporate (emitting gamma-rays) on times comparable or shorter than lifetime of Universe

BH would induce “interferometry” pattern in the energy spectrum of lensed GRBs

PBH capture in stars catalyze fast conversion in BH, while “old” evolved objects like WD or NS are observed (DM-density dependent bound)

direct searches via micro-lensing, plus other arguments (do not strictly require them to be BHs)

bounds from CMB spectral distortions, secondary anisotropies induced (e.g. reionization) either via accretion byproducts or by explosive runaway instability (if rotating, due to “plasma mass”)
Although limits can be weakened a bit for PBH masses distributed over many decades, the best hope to evade them is to assume that a sizable evolution of the mass function takes place (e.g. born sub-solar, thus evading CMB constraints, merging to tens of $M_{\odot}$, to evade lensing).

Recently, this way out has been shown to be on shaky grounds!

CMB excludes that more than 3-4% of DM (of any mass) has converted into any invisible radiation (like GW), over the whole history from recombination to now!

either PBH do not make a sizable fraction of the DM or their mass function evolution should be negligible: in the two merger events seen by LIGO ∼5% conversion of mass into GW!
**Microlensing**

**idea:** Compact object crossing along the los acts as a gravitational lens, inducing a time-dependent magnification pattern depending on the geometry and mass. From limits to the rate of such events, DM fraction limits to the associated mass.

\[ A(u) = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \]

\[ u = \frac{\theta}{\theta_E} \]

\[ \theta_E = \sqrt{\frac{4GM}{c^2} \frac{d_S - d_L}{d_S d_L}} \]

\[ u(t) = \sqrt{u_{\text{min}}^2 + \left(\frac{t - t_0}{t_E}\right)^2} \]

ang. distance source-lens depends on lens mass and geometry

t_E = time to cross Einstein angular size

Several searches (EROS, OGLE...) for μlensing events towards Magellanic Cloud exclude dominant MACHOs component as halo DM from 10^{-7} to 10 M_{\odot}

E.g. L. Wyrzykowski et al., arXiv:1106.2925 & refs. therein
some events expected due to stellar BH
EXAMPLE OF LIMITS ON “MACHOS”

Too large DM “particle” would disrupt bound systems of different orbital sizes (function of mass) via associated time-dependent gravitational potentials

- thickness of disks: \( M_X < 10^6 \, M_\odot \)
- satellites, globular clusters: \( M_X < 10^3 \, M_\odot \)

- Halo-wide binaries: Method proposed in
  Latest bound \( M_X \lesssim 100 \, M_\odot \) to \( \lesssim 5 \, M_\odot \)
  (for higher and higher “binary quality” cuts)

\[ H-W.\text{Rix and G. Lake, astro-ph/9308022} \& \text{refs. therein} \]


\[ \text{EXAMPLE OF LIMITS ON “MACHOS”} \]

\[ H-W.\text{Rix and G. Lake, astro-ph/9308022} \& \text{refs. therein} \]


Presence/stability of stellar systems in ultra-faint dwarf Galaxies close the 20-100 $M_\odot$ window (notably a stellar cluster in Eridanus II could push the limit to $\sim 3$ $M_\odot$, barring $\sim 1\%$ chance alignments)

T. D. Brandt,
“Constraints on MACHO Dark Matter from Compact Stellar Systems in Ultra-Faint Dwarf Galaxies,”
Dark Matter requires “new physics”, beyond known theories, in order to be produced, and most likely is made of new degrees of freedom itself!

Only a handful of similar indications for BSM: explains the interest of particle physicists!

Cosmology and astrophysics also give us some “particle physics” constraint

- How much DM is out there
- DM is not “hot” (non-relativistic velocity distribution… as for the neutrinos)
- Must be stable or long-lived
- DM must be sufficiently heavy
- DM... is dark, and dissipationless
- DM is collisionless (or not very collisional)
- DM has small interactions with ordinary matter

let us review these constraints. We assume everywhere that there is a single species accounting for (most of) DM. Multi-component is certain (at least v’s!) but one expect one to dominates (in the SM sector, for instance, it happens!), to prevent further “fine tuning”
Recent determination (Planck 2015, 68% CL)

\[ \Omega_c h^2 = 0.1188 \pm 0.0010, \text{ i.e. } \Omega_c \sim 0.26 \]

\[ \rho_{X,0} = M_X n_{X,0} = M_X s_0 Y_0 \]

\[ \rho_c = \frac{3H_0^2}{8\pi G_N} = 1.054 \times 10^{-5} h^2 \text{GeV cm}^{-3} \]

\[ s_0 = 2889 \left( \frac{T_{\gamma,0}}{2.725} \right)^3 \text{ cm}^{-3} \]

where \( h_{\text{eff}} \sim 2 + 3 \times 2 (4/11) \times 7/8 \sim 3.91 \)

comes from accounting for \( \gamma \)'s & \( \nu \)'s

\[ \Omega_X h^2 = 2.74 \times 10^8 \left( \frac{M_X}{\text{GeV}} \right) Y_0 \]

**[Main] Goal (Lec. 3-4-5)**

compute value of number to entropy density ratio, \( Y_0 \)
Stringent bounds from astrophysics if decaying into “visible” species \((e^\pm, \gamma) \approx 10^{27} \text{ s}\) (Calore’s lectures)

Even, if decaying into invisible channels, bounds still exist from CMB & Large Scale structures (under the sole assumption of relativistic byproducts)

CMB mostly affected by late integrated Sachs-Wolfe effect (modification of homogeneous & perturbed DM density at late times affects evolution of metric fluctuation) LSS helps in breaking partial degeneracy with curvature & tensor modes

\(\tau \gtrapprox 160 \text{ Gyr} \) (CMB only)
\(\tau \gtrapprox 170 \text{ Gyr} \) (with other consistent data)

B. Audren et al. JCAP 1412, 028 (2014) [1407.2418]

V. Poulin, PDS, J. Lesgourgues, arXiv:1606.02073

at very least one order of magnitude longer than age of the universe
LOWER LIMIT ON DM MASS

**dark matter is confined/detected at least at astrophysical scales, hence must be “localized” and behave classically there.**

\[
\lambda_{\text{De Broglie}} = \frac{\hbar}{mv} \lesssim \text{kpc} \implies m \gtrsim 10^{-22} \text{ eV} \ (v \approx 100 \text{ km/s})
\]

For **fermions** a much stronger bound holds, due to the fact that they obey Fermi-Dirac statistics (“Pauli principle”)

\[
f \leq \frac{g}{h^3}
\]

Conservation of phase space density of a non-interacting fluid (Liouville Eq.) + condition that any observable, coarse grained p.s. density must be lower than the real one, in turn lower than the above maximum, one derives

\[
m > \mathcal{O}(10 - 100) \text{ eV}
\]


updated lower limit around \(~400 \text{ eV}\

*A. Boyarsky, O. Ruchayskiy and D. Iakubovskyi, JCAP 0903, 005 (2009)
EXERCISE

Consider a spherical, uniform system, gravitationally bound, of mass $M$ and radius $R$, made of “cold” fermionic particles of mass $m$, with $g$ spin dof. Compute the lower limit on $m$

**Hints/Guidelines**

*gravitationally bound*: all particles should have a velocity lower than the gravitational escape velocity (compute the latter for such a system)

*cold fermions*: the system contains $N=M/m$ particles. But the “coldest” fermion system still settles in “Fermi levels”… compute the Fermi velocity as a function of $M, R, m, g$.

*estimate*: Given the dependence on $M, R$, which systems are optimal to set bounds on $m$? Search the literature for typical values of $M, R$ of astrophysical systems (clusters of Galaxies, Milky Way-like Galaxy, dwarf spheroidals) and to derive an order of magnitude bound

**Bonus**: Direct (terrestrial) experiments tell us that neutrinos have a maximum allowed mass of about 2.2 eV. What’s the maximum overall mass they could contribute to a Milky Way-sized halo (assuming that they can be “maximally packed” into it)? What if the forthcoming Katrin experiment pushes the upper limit to 0.2 eV, as expected?
DM is... dark and dissipationless

DM must not couple much to γ’s (perturbation shape & amplitude argument, not seen in e.m. channels…). Neither it can couple to its own “invisible photons” exactly like baryons!

Why? For instance, because DM forms extended, triaxial halos, while baryons “sink” in inner halo parts, form disks, etc. since they can dissipate energy by e.m. emission. At Galactic scale, evidence from tidal streams of satellite galaxies (some diagnostic also via lensing…)

To make the argument quantitative, simulations needed. Details do matter (plenty/all of them) e.g. the baryonic disk does make the DM one “more spherical”…


Don’t get confused about claims of a possible “dark disk”, maybe related to mass extinctions!

  e.g. L. Randall and M. Reece, “Dark Matter as a Trigger for Periodic Comet Impacts,” PRL 112, 161301 (2014) [1403.0576]

The bulk of DM must be dissipationless! Some room for sub-leading component (<5% according to J. Fan, A. Katz, L. Randall and M. Reece, “Dark-Disk Universe,” PRL 110, 211302 (2013) [1303.3271]) which is dissipative and may form ‘disks’. To call it the DM is as accurate as saying that missing baryons or standard neutrinos are the DM.

  Further constraints from “dark oscillations”
DM IS COLLISIONLESS (WRT BARYONIC GAS)

- if DM-DM interaction too strong, spherical structures would be obtained rather than triaxial. From actual clusters, one can derive $\sigma/m<0.02$ cm$^2$/g
  

- From Bullet cluster, $\sigma/m<0.7\text{-}1.3$ cm$^2$/g,
  

- similar bounds from different arguments, for a compilation see e.g.

<table>
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<tr>
<th>System</th>
<th>$v_0$[km/s]</th>
<th>$\sigma/m_\chi$ [cm$^2$/g]</th>
<th>References</th>
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<td>[41, 43]</td>
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<td>[45]</td>
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<td>0.01 – 0.6</td>
<td>[57]</td>
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<tr>
<td>Dwarf Galaxies</td>
<td>10</td>
<td>0.1</td>
<td>[56]</td>
</tr>
</tbody>
</table>

- Very loose from particle physics standard (barn/GeV level), but much less than atomic or molecular cross sections!


\[
\frac{\text{cm}^2}{\text{g}} = 1.78 \frac{\text{barn}}{\text{GeV}}
\]

**Exercise:** estimate the geometric cross section for hydrogen atomic scattering… & compare!
ACTUAL SIMULATIONS NEEDED...& COMPLICATIONS

• For instance, ref. A. H. G. Peter, M. Rocha, J. S. Bullock and M. Kaplinghat, B. MNRAS 430, 105 (2013) [1208.3026] found that, while interactions among dark-matter particles will drive galaxy and cluster halos to become spherical in their centers, DM self-interaction cross sections at least as large as $\sigma/m = 0.1 \text{ cm}^2/\text{g}$ are allowed

• Typically, such large $\sigma$ require a light mediator (at least if one wants to stay perturbative), sort of “dark photon” (can be massive, though) $\Rightarrow$ velocity dependent $\sigma$ implied (smaller in clusters!)

L. G. van den Aarssen, T. Bringmann and C. Pfrommer, PRL 109, 231301 (2012)[1205.5809]
...
• some collisional aspects may be beneficial for possible issues of CDM paradigm at small scales, on core sizes and central densities of dwarfs, LSBs, and galaxy clusters e.g.

M. Kaplinghat, S. Tulin and H. B. Yu,
“Dark Matter Halos as Particle Colliders: Unified Solution to Small-Scale Structure Puzzles from Dwarfs to Clusters,” PRL 116, 041302 (2016) [1508.03339]

• New simulations with dark radiation currently being developed, see e.g.

T. Sepp et. al. “Simulations of Galaxy Cluster Collisions with a Dark Plasma Component” arXiv:1603.07324

non-interacting DM distribution displayed in blue (80%), dark plasma (20%) in red.

Bottom line: DM should not have self-interactions exceeding the barn/GeV level; slightly smaller $\sigma$ could also be beneficial… however be aware that the relevant scales are affected by baryonic effects, feedbacks, etc. Unclear to isolate smoking guns (and simulations with both baryons and collisional DM eventually needed)
DM COUPLING TO NORMAL MATTER

Same bounds as before also apply (order of magnitude!), plus a number of additional ones

By the way, if DM is a fundamental particle, \( M < M_{\text{Pl}} \sim 10^{19} \text{ GeV} \) (higher, would be a BH!)
But could be an exotic composite state! similar bounds as for BH apply down to \( \sim 4 \times 10^{24} \text{ g} \) (or \( 10^{-8} M_\odot \)), and sometimes below that. Extra bounds exist. For details see


Too strong coupling with photons damp CMB anisotropy tail \( \sigma_{\text{DMV}}/m = 8 \times 10^{-31} \text{ cm}^2/\text{GeV} \)
and with neutrinos, suppressed Ly \( \alpha \) power spectrum \( \sigma_{\text{DMV}}/m = 8 \times 10^{-33} \text{ cm}^2/\text{GeV} \)

SUMMARY OF WHAT WE LEARNED

- Hopefully, some **clarification** on the (partially) misleading **dichotomy DM vs Modified Gravity**: the key is the need for some new degree of freedom.

- It turns out that this requires **new physics** (even for-the highly constrained-BHs, need some exotic production mechanism) with some specific properties.

- Astrophysical and cosmological arguments put some constraints on DM. Unfortunately, cannot get “too far” since “gravity is universal” ➔ it does not tell us what the underlying new physics is.

- We need some “strategy” to identify what DM is. For that, first we need some extra input/constraint ➔ must necessarily come from theory, i.e. let’s try to define some classes of candidate: We Shall classify them via **production mechanisms**, the **leitmotif** of Lectures 3-4-5.